SEPARATING EARLY SPLIT FROM NORMAL PISTACHIO NUTS FOR REMOVAL OF NUTS CONTAMINATED ON THE TREE WITH AFLATOXIN

BY
Tom C. Pearson
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ABSTRACT

The hull of an early split pistachio nut abnormally splits open on the suture approximately 30 to 60 days before harvest at the same time the shell splits open. The kernels of these nuts have been shown to contain nearly all of the aflatoxin in pistachio orchards (Sommer et al., 1986). Presumably, *Aspergillus flavus* molds contaminate early split nuts because of the easy access to the kernel through the hull opening. Early split pistachio nuts comprise 1% to 4% of the crop so removal of these nuts to rid the pistachio crop of aflatoxin could be an economically viable method. Normal nuts are predominately (80%) comprised of nuts with no visible lesions on their hulls, with 20% of the normal nuts exhibiting hull lesions occurring close to harvest. Normal nuts do not contain significant levels of aflatoxin (Sommer et al., 1986).

The physical properties of early split and normal pistachio nuts were evaluated to determine if a sorting criteria to remove early split nuts from the crop could be developed. The physical properties data showed that early split nuts are significantly smaller in length, width, height, mass and volume than normal nuts. However, discriminate analysis showed that these properties, used alone or in combination, cannot achieve an accurate segregation between classes. But, these properties may be useful to enhance sorting accuracy with other methods. Unhulled nut moisture content, density, hull thickness, terminal velocity, and hull friction factor are not significantly different between early split and normal nuts.

Early split nuts were found to have more shell staining than normal nuts. Early split nuts are particularly prone to either a yellowish stain all over the shell or a dark brown stain adjacent to the suture split on the shell. Shell color was measured on a 3 mm diameter spot at the apex of the suture split on pistachio nuts. This spot often, but not always, contains a portion of the dark brown suture stain characteristic of early split nuts. Discriminate analysis showed that approximately 82% of the early split nuts could be distinguished from normal nuts while only 7% of the normal nuts would be incorrectly classified using shell color. Nuts were also inspected for stains adjacent to the shell suture split or for a yellowish hue covering at least 90% of the shell. When this categorical data was combined with the length and width of the pistachio shell, it was found that 90% of the early split nuts and 93% of the normal nuts were correctly classified.

Early split nuts were found to have a strong tendency for their hulls to adhere to their shells. Two devices were constructed to test the hulling characteristics of pistachio nuts. One device, called the spin huller, operated similarly to a small potato peeler. It consisted of a horizontal abrasive rotating disk enclosed within a vertical cylinder lined on the inside with sandpaper. The other device tumbled nuts at a slow speed in a large drum. After 20 seconds in the spin huller, 98% of the normal nuts were hulled while only 7% of the early split nuts lost their hulls. After 180 seconds in the tumbler, 99% of the normal nuts became hulled while only 9% of the early split nuts lost their hulls. It appears that hulling characteristics can be used to separate early split nuts without drastically changing current pistachio processing practices. Nuts that do not hull could be separated in color sorters or by a floating treatment.

Two devices were developed to convey and orient unhulled pistachio nuts for presentation to a computer vision system. One device operated similar to an "air hockey" table. It raised the nut on a cushion of air and oriented it so that its suture plane was in the horizontal plane. This device correctly oriented 98% of the early split nuts and 99% of the normal nuts. The other device used vibration to move and orient the nut in a V trough. This device correctly oriented 97% of the early split nuts and 98% of the normal nuts.

An investigation using computer vision to detect early split lesions on the hull of pistachio nuts was performed. Gray scale intensity profiles were computed across the width of the nut (perpendicular to the suture). If the profile crossed an early split lesion, a deep and narrow valley on the profile at the early split location was observed. Profiles were computed every 0.5 mm along the nut and the number of adjacent profiles with deep and narrow valleys was recorded. Early split nuts contained a significantly higher count of adjacent profiles than normal nuts. Combining the unhulled nut length and width dimensions to the adjacent profile data, discriminate analysis showed that 100% of the early split nuts and 99% of the normal nuts could be correctly classified.

1. INTRODUCTION

Pistachio nuts have become an increasingly important crop in California over the last 17 years. Pistachio acreage in California has increased from 1,666 in 1977 to 52,073 in 1991. During the same time, the value of the crop has increased from $4,680,000 to $100,716,000 (California Pistachio Commission, 1993). Nearly all of the pistachios grown in the United States are grown in California. The United States is second only to Iran in pistachio production. In 1992, 145.5 million pounds of processed pistachios were grown in the United States (California Pistachio Commission, 1993). Pistachios are an important export commodity for California. In 1992, California exported 25.9 million pounds of inshell pistachios. The chief export destinations are Germany, Hong Kong, Japan, Canada, and Taiwan (California Pistachio Commission, 1993).

While growing on the tree, the shell of the pistachio nut is enclosed in a hull, much like a walnut or almond. The characteristic split on the shell of a pistachio occurs while the nut is still on the tree, about a month before harvest. After the shell splits open, the hull normally remains intact and serves as protection for the kernel from mold spores and insect infestation. However, on about 1% to 4% of the crop, a lesion on the hull suture can occur when the shell splits open. These are called "early split" pistachio nuts. Early split nuts are found to be susceptible to aflatoxin contamination (Sommer, 1986). Figure 1.1 displays an early split nut in a cluster of pistachio nuts on the tree.

Presumably, the lesion on the hull allows spores of the aflatoxin producing mold, *Aspergillus flavus*, to enter the nut and grow on the kernel. Nearly all of the pistachio nuts contaminated on the tree are of the early split type (Sommer, 1986). Thus, removal of this type of nut could be an economically viable method to rid the pistachio crop of aflatoxin. Concern is increasing about the health and economic impact of aflatoxin in pistachio nuts. The European Community is tightening its regulations for aflatoxin content in imported commodities. As a result, export shipments of pistachio nuts from California have been rejected on occasion because of aflatoxin.

There has been no documented investigation of the physical properties of unhulled pistachio nuts. Furthermore, there has been no investigation comparing the properties of early split nuts to normal nuts.

Objective

The purpose of this study was to evaluate the physical properties of pistachio nuts and determine features for distinguishing early split nuts. When the physical properties were documented, methods for separating early split pistachio nuts were explored.

Figure 1.1. Early split pistachio nut on the tree

2. LITERATURE REVIEW AND BACKGROUND

Pistachio Processing

Pistachios grown in California are harvested during a two to three week period in September. The nuts are ready for harvest when the hulls become easily separated from the shells. Premature harvest causes a high percentage of undeveloped kernels while a late harvest results in more nuts with shriveled hulls, more shell staining, and increased incidence of fungus infestation (Kader, 1990). Pistachios are harvested by shaking the tree and catching the nuts onto a sloping collector (canopy). The nuts roll down to a conveyor which transports them to a bin carried behind the harvester (Crane, 1977). The nuts are then transferred to a larger trailer bin to be taken to the processing plant. Normally, the nuts will be delivered to the plant within 24 hours after harvest from the tree. At the plant, unwanted waste such as leaves and twigs are removed and the nuts are hulled (Bloch, 1960). After hulling, the nuts may be immersed in water where hulled nuts with split shells will sink while hulled nuts with unsplit shells, unhulled nuts and hull material will tend to float. The nuts may also pass through a pneumatic sorter to accomplish this same separation. Then, the nuts will be dried. Most processors currently use heated air at 60°C to 71°C for 10 to 14 hours to dry the nuts to 5 to 7% moisture content (Kader, 1990). The nuts are then put into dry storage for processing throughout the remaining year.

After the rush of the harvest season has subsided, the nuts are taken from storage, graded into sizes, and passed through color sorters (both human and electronic) to remove stained nuts and incompletely hulled nuts. The electronic color sorters are actually monochrome devices that distinguish stains from shell material by comparing the nut with a shell colored background. The stained and unhulled nuts may then be either shelled and sold to be used for processed products (e.g. ice cream or cake mix) or they may be stained a dark red to cover the blemishes on the shell. The unblemished nuts are roasted, salted, and packaged (Kader, 1990).

Crane (1977) gives a good general background of pistachio cultivating and processing: The fruits of a pistachio are classified as drupes, the same type of fruit as almonds, apricots, cherries, plums and peaches. There are several species of pistachio trees, but, *Pistachia vera* is the only species that produce fruits large enough to satisfy customers.

Also, *P. vera* is the only pistachio species in which the shell (endocarp) splits along the suture. Pistachio trees are alternate bearing, producing a heavy crop in one year followed by a light crop the next. The pistachio cultivar of choice used almost exclusively in California is called Kerman. This cultivar was developed by the US. Department of Agriculture in 1929 from Iranian and Turkish seeds. The Kerman cultivar thrives in California's hot and dry San Joaquin Valley. While the Kerman cultivar is known for its high yield capacity and its large nuts, it is also known for its highly biennial production.

A large scale pistachio processing plant has an unhulled nut throughput on the order of 1.5 million pounds per 24 hours during the harvest season. This is roughly 2250 nuts per second. Any sorting device or method for unhulled nuts will have to be able to accommodate this magnitude of throughput.

Aflatoxin

Aflatoxin is a secondary metabolite of the mold, *Aspergillus flavus*; it is known to infest several commodities such as dairy products, corn, rice, soybeans, peanuts, pecans and pistachio nuts (Ciegler, 1975). Aflatoxin is known to cause liver damage in humans, reduce growth rate and cause immunosuppression at levels of 1 part per million in the diet of domesticated and experimental animals (CAST, 1979). Aflatoxin has caused deaths in farm animals that consumed heavily contaminated feed (Farsaie et al., 1981). Aflatoxin caused hepatitis and death in more than 100 people who consumed severely contaminated maize (Samarajeewa et al., 1990); however, it is not common to find food contaminated with aflatoxin to the degree that it will cause immediate health problems. But, aflatoxin is also a known carcinogen that has been traced to increased chances of liver cancer after repeated consumption of low levels (above 20 ppb.) of contaminated food (Samarjeewa et al., 1990). Dichter et al. (1984) estimated that due to aflatoxin exposure in the United States, 58 to 158 people per year are inflicted with liver cancer. However, Yeh (1989) reported that, in southeast China where food regularly contains high aflatoxin concentrations, 91% of the liver cancer deaths in this area were in people who also tested positive for hepatitis B_1. Thus, people likely to be inflicted with liver cancer due to aflatoxin may also have had hepatitis B_1.

Aflatoxin may remain in foods for a very long time after the *Aspergillus flavus* has died and disappeared. Dangerous levels of aflatoxin may be present in foods that are not visibly moldy. Furthermore, *Aspergillus flavus* molds can thrive in a range of conditions

from a hot arid climate to warm and humid conditions. *Aspergillus flavus* thrives particularly well in southeast China and in southeast Africa (CAST, 1979). Liver cancer is known to be more likely in these areas as well.

The commercial practice to screen most nuts (pecans, peanuts, etc.) for aflatoxin is to remove stained, blemished, or insect damaged nuts with color sorters. Stoloff (1980) estimates that 66% of the aflatoxin contaminated peanuts are removed by standard sorting and processing practices. Many of the aflatoxin contaminated peanuts can be removed by color sorting. Dickens and Whitaker (1975) report that as much as 72% of the aflatoxin in a peanut crop could be removed by color and hand sorting. However, not all peanuts that are discolored will have aflatoxin and not all aflatoxin contaminated peanuts will be discolored. Color sorting is useful to reduce the amount of aflatoxin in the crop, but cannot eliminate it.

Aspergillus flavus also excretes kojic acid which, after reaction with plant tissue, is fluorescent after ultra-violet illumination (Marsh, 1969). This property has been used to develop sorting devices for aflatoxin contaminated commodities. For example, Tyson et al. (1974) developed a sorter for pecans using this property. Pelletier et al. (1991) developed a high speed peanut sorter that examines individual peanuts for fluorescence at a rate of 360 per minute. Farsaie et al. (1981) and McClure et al. (1980) developed an automatic sorter for unshelled pistachio nuts. However, it has not yet been shown that there is a direct correlation between aflatoxin content and florescence. Fennell et al. (1973) found non-fluorescent white corn kernels that contained greater than 3000 ppb. aflatoxin, and fluorescent kernels with aflatoxin contents less than 20 ppb. Steiner et al. (1992) found similar results for pistachio and brazil nuts. There are several other molds that excrete kojic acid, causing false alarms for aflatoxin. Thus, these machines are not currently being commercially utilized as they may not remove badly contaminated nuts and they may remove many acceptable nuts.

The majority of aflatoxin in corn can be removed by careful milling practices. Most of the aflatoxin present in corn is in the germ, hull, and degerm fines (CAST, 1979). When corn is wet milled, the starch contains only about 1% of the original aflatoxin while the feed products contain about 97% of the original aflatoxin (Bennett, 1976).

Ammonia can significantly inhibit *Aspergillus flavus* growth and inactivate the toxic affects of aflatoxin (Rodricks, 1977). In a combined heat (145°C for 3 hours) and

ammonia treatment, 99% of the aflatoxin in corn was destroyed (Conway, 1978). When seed kernels are pressed for oil, some of the aflatoxin will also be released into the oil. Aflatoxin in cottonseed oil was deactivated by using a solution of 1.5% ammonium hydroxide without causing any harmful by-products (Lough, 1979).

Aflatoxin is stable up to its melting point of 250°C. However, some degradation of aflatoxin can occur at extended exposure to temperatures lower than 250 °C (CAST, 1979). Rodricks et al. (1977) reported that 80% of aflatoxin in cottonseed was destroyed when heated to 100°C for two hours. However, the heating also darkens the grain and adversely affects the protein quality.

There is work being done to control aflatoxin by introducing mold to the growing crops that will compete with *Aspergillus flavus* (CAST, 1979). Cole (1992) is experimenting with a strain of *Aspergillus parasiticus* that does not produce aflatoxin. In a three year test, they treated one peanut field with the non-aflatoxin producing *Aspergillus parasiticus* strain and left an adjacent field untreated. Peanuts from the treated field contained average concentrations of 11, 1, and 40 ppb. aflatoxin in the three year study. However, the untreated field contained aflatoxin concentrations of 531, 96, and 241 ppb during the same three years, respectively.

Currently, research is underway in India to investigate use of onion and garlic extracts as an inhibitor for *Aspergillus flavus* growth. Preliminary results indicate that onion extract could reduce aflatoxin production by 60% (Bilgrami, 1992). In another area, Harvey (1989) reports that hydrated sodium calcium aluminosilicate, an inert anti-caking substance used in feeds also can help reduce aflatoxin build up in milk. The additive binds the aflatoxin in the animal's intestine. When the 1% aluminosilicate was added to heavily aflatoxin contaminated feed (100 ppb.) a 54 to 60% reduction in expected aflatoxin concentration in the milk was observed.

Pistachio Nuts and Aflatoxin

Pistachio nuts are characterized by a split in the shell at the calyx end of the nut. This split normally occurs on the tree about a month before harvest. The hull (mesocarp) of the pistachio usually encloses the shell and remains intact through harvest, serving as protection for the kernel. On normal nuts, there is space between the hull interior and shell exterior, so the shell can split open without splitting the hull. However, about 1% to

4% of the time, the hull will adhere tightly to the shell and the hull will split open along with the shell. These nuts are called "early splits". The split in the hull allows an unobstructed passage to the kernel for airborne mold spores and insects or other small animals, such as mites, that might be carrying mold spores (Sommer et al., 1986). Insects and small animal infestation rates on early split nuts are much higher because of the easy access to the kernel. The mold, *Aspergillus flavus*, has been found in pistachio nuts before harvest (Thomson et al., 1978). Sommer et al. (1986) showed that nearly all the *Aspergillus flavus* contaminated nuts also have split, insect damaged, or bird damaged hulls before harvest. Sommer et al., found the incidence of aflatoxin contamination to be about fifty times greater in early split nuts than in non split nuts (1 in 500 for early split nuts versus about 1 in 25,000 of all nuts). The aflatoxin contaminated non split nuts studied by Sommer et al. were found to be contaminated at the lowest levels of detectability (less than 2.0 ppb) while many early split nuts were found to contain aflatoxin concentrations greater than 20 ppb and some above 1000 ppb. The US. Food and Drug Administration's allowable limit for aflatoxin content in peanuts for human consumption is 20 ppb and 0.5 ppb for milk (CAST, 1979).

The prominent physical characteristic of an early split pistachio is a distinct, dark and smooth edged split on the suture of the hull (see figure 2.1). When an early split occurs, the split will normally start at the calyx end of the hull and be present on only one side of the nut. An early split can occur as early as 60 days before harvest but most occur from 30 to 20 days before harvest. Nuts in which the hull splits 60 to 30 days before harvest have a much greater opportunity for *Aspergillus flavus* infestation and high levels of aflatoxin, since the mold has had a much longer time to grow and excrete aflatoxin. These nuts, with the split in their hull for an extended period of time, tend to be drier than normal nuts or other nuts whose hulls split closer to harvest. Doster et al. (1991) found that early split nuts with dry, shriveled hulls were three times more likely than other early split nuts to be infested with *Aspergillus flavus*. Furthermore, aflatoxin was found in 31% of the shriveled early split nuts at an average concentration of 31 ppb, and aflatoxin was seen in only 6% of the non-shriveled early split nuts at an average concentration of 0.4 ppb (Doster et al., 1993).

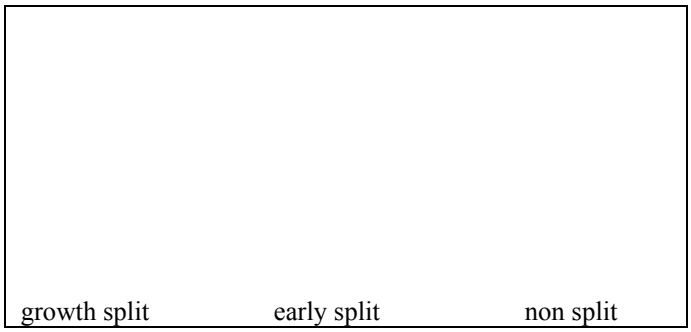

Figure 2.1. The three pistachio hull split types

Another kind of split that can occur on a pistachio hull shortly (less than 15 days) before harvest is called a growth split. Growth splits on pistachio hulls are characterized by ragged brown edges, and the split is randomly oriented and much wider than an early split (see figure 2.1). It has been shown that these nuts do not contain aflatoxin or *Aspergillus flavus* at harvest time, presumably because the mold has not had time to develop (Sommer et al., 1986). For the purposes of this study, growth split nuts are not considered a health risk and are classified as normal nuts along with non split nuts. However, because of their morphological differences, their physical properties are discussed separately.

Doster et al. (1993) observed that early split pistachio nuts tend to have shell stains near the perimeter of the shell suture split. Furthermore, Doster reports that early split nuts with shell staining had a higher incidence of *Aspergillus* molds than non-stained early split nuts. However, in the same study, as much as 12% of the early split nuts that were contaminated with *Aspergillus flavus* had only slightly visible shell stains. Figure 2.2 shows a typical early split shell stain.

As stated earlier, *Aspergillus flavus* is also prevalent in bird and insect damaged nuts. Doster et al. (1993) found that 15.4% of the insect damaged pistachio nuts had *Aspergillus flavus* spores while only 2.4% of the non-insect infected nuts contained spores. These nuts often have abnormally low densities and are removed in a normal pistachio processing plant with existing quality control equipment (Kader et al., 1980). Therefore, bird damaged and insect damaged nuts are not included in this study. The non-damaged early split nut densities are indistinguishable from normal nuts so they are not removed during normal processing.

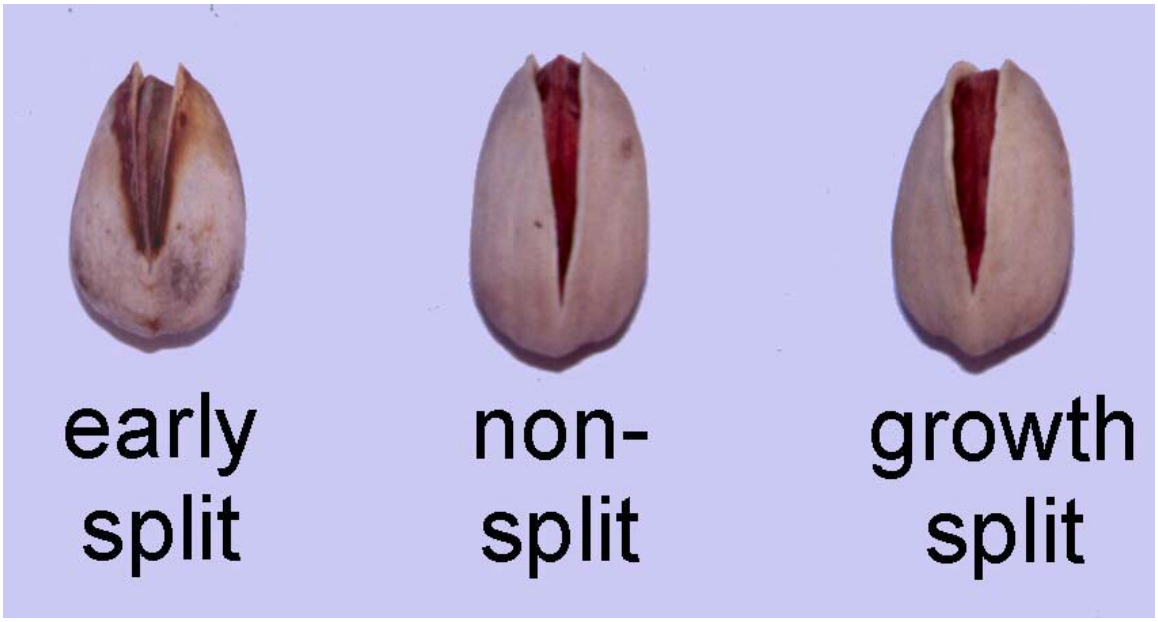

Figure 2.2 Early spilt shell stain

Danesh et al. (1979) showed that there will be a higher incidence of aflatoxin contamination if it rains about a month before harvest, when early splits occur. It is evident that high humidity will enhance *Aspergillus flavus* growth. The weather in California's San Joaquin Valley, where most pistachios are grown, is normally dry. Doster et al. (1993a) found that an individual orchard's irrigation and cultural practices have little effect on the quantity of early split nuts in the orchard. Some orchards are flood irrigated and some are drip irrigated, and some orchards are neatly disked to keep weeds down while others are not. These factors do not seem to greatly affect the amount of early splits in the orchard. However, Michailides (1993) showed that sprinkler irrigated pistachio orchards using high trajectory sprinklers (above 23°) can increase the chance of Botryosphaeria blight. This disease can cause small black lesions on the pistachio hull. The risk of Botryosphaeria blight is reduced when the sprinkler trajectory is reduced so that it does not wet the nut clusters. It is not known if there is a correlation between Botryosphaeria blight and *Aspergillus flavus* contamination.

Physical Properties of Pistachio Nuts

There is little published work on the physical properties of pistachio nuts, particularly with regard to unhulled nuts. The physical and thermal properties of hulled pistachios were investigated by Hsu (1991). Hsu's paper reports the bulk density, specific heat, thermal conductivity, specific gravity, surface area bulk thermal diffusivity and moisture content of hulled pistachio nuts. Crane (1977) reported the nutrition value of pistachios.

The only published work comparing the properties of early split nuts with normal nuts is by Doster (1993). This report shows that early split nuts with and without *Aspergillus flavus* molds are significantly smaller in shell length and mass than normal nuts. However, Doster's study showed that there is no relation between presence of *Aspergillus flavus* molds and significant differences in early split nut properties. The likelihood for early split nuts to have dark stains adjacent to their shell suture and *Aspergillus flavus* contamination rises for earlier hull splitting dates. They also found that moisture content drops for early split nuts with earlier hull splitting dates.

Color Theory

There are several systems for describing color. A human's method for describing color is normally in terms of brightness, hue, and saturation. The sensation of brightness describes the luminous flux or light intensity or grayness (black, grey or white). Hue indicates the dominate wavelength and describes the color as red, blue, green, orange, etc. (Benson, 1986). Saturation describes the sensation of the color's strength or purity (pale, pastel, vivid, strong). A person might describe a purple flower as "bright, vivid purple". In doing so, he is indicating the brightness, hue and saturation respectively. The descriptors of dominate wavelength (hue) and color purity (saturation) are often jointly referred to as the chromaticity (Loughlin, 1986).

Computer vision often uses a system called RGB color. This system describes the color of a light as a mixture of red, green, and blue regions of the spectrum at various intensities. White light would contain all wavelengths in the spectrum. Computer vision uses the additive properties of light and not the subtractive properties of paints. White paint cannot be produced by combining colors of different paints, but white light is achieved by the additive primaries of red, green and blue light (McGinty, 1984)

It is possible to match the color stimulus by combining different levels of three primary stimuli (Benson, 1986). The color C can be "matched" by r units of primary R, g units of primary B and b units of primary B as shown in equation 1. Any set of primary stimuli can be used, the only requirement is that an individual primary stimuli cannot be matched by a combination of the other two. The RGB system uses stimulus from real red, green, blue primaries with wavelengths of 700.0 nm, 546.1 nm, and 435.8 nm respectively. However, this system must use a negative quantity of the red primary.

$$C = rR + gG + bB \qquad (1)$$

In 1931, the International Commission on Illumination (I.C.I.) agreed upon a system to describe color using imaginary primaries obtained by mathematical methods. This system was developed by experimental data from many observers. The standard I.C.I. color mixture curves are shown in figure 2.1. Note that a negative primary is not needed in the visible light range. The values of the $\bar{x}$, $\bar{y}$ and $\bar{z}$ curves at an individual wavelength are called the tristimulus values. The $\bar{x}$ values indicates the "redness" of the light while the $\bar{y}$ and $\bar{z}$ values indicate the "greenness" and "blueness" respectively.

For a light containing a range of wavelengths, the tristimulus values for each wavelength are added to obtain the chromaticity coordinates of the light's color. The tristimulus values for a range of light wavelengths are denoted using X, Y and Z. If $f(\lambda)d\lambda$ is the radiant flux at wavelength λ in a sample of light, then the tristimulus values are computed using equation set 2 (Sears, 1958). Values of the $\bar{x}$, $\bar{y}$ and $\bar{z}$ functions are tabulated in many texts (e.g. Driscoll, 1978) and the integration can be computed numerically.

$$X = \int_{380}^{780} \bar{x} f(\lambda) d\lambda \qquad Y = \int_{380}^{780} \bar{y} f(\lambda) d\lambda \qquad Z = \int_{380}^{780} \bar{z} f(\lambda) d\lambda \qquad (2)$$

The chromaticity coordinates are then computed using equation set 3 (Benson, 1986). Any two of the trichromatic coefficients are adequate to define color since by their definition their sum equals 1. Normally, x and y are used (Sears, 1958).

$$x = \frac{X}{X + Y + Z} \qquad y = \frac{Y}{X + Y + Z} \qquad z = \frac{Z}{X + Y + Z} \qquad (3)$$

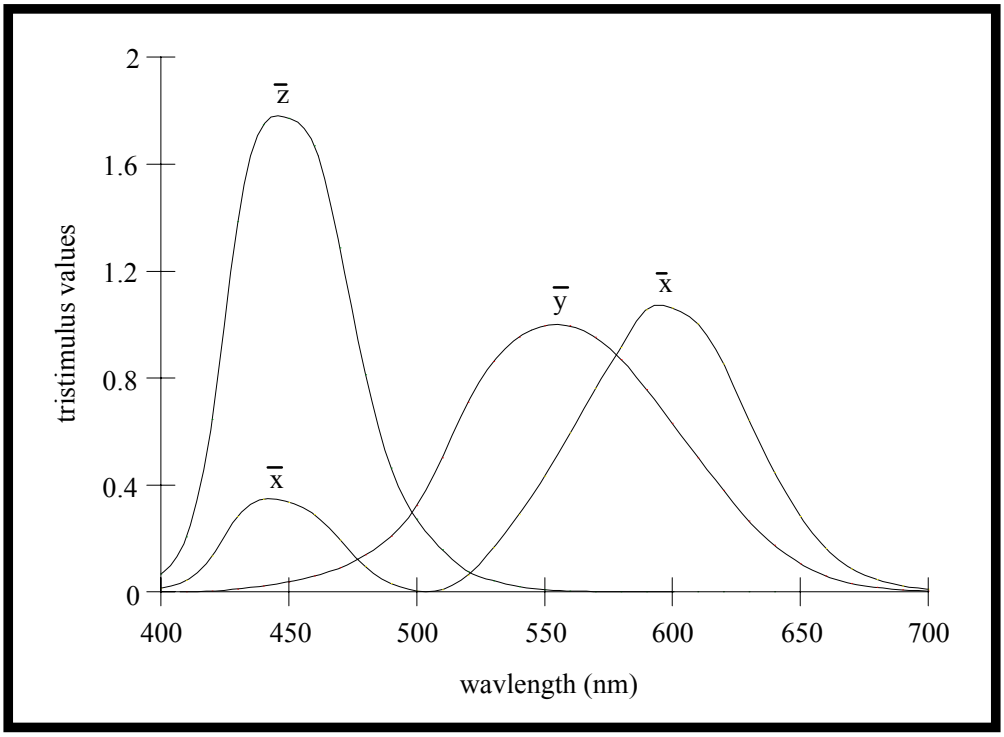

Figure 2.2. Tristimulus curves

Computer Vision

A plausible method for separating early split pistachio nuts from normal nuts is to detect early split lesions on the hull with a computer vision system. Several computer vision systems have been developed to inspect products at high rates. Ball Metal Container Corp. (Arvada, CO) has developed a computer vision system to inspect beverage cans for dents at a rate of 30 cans/s. Tang et al. (1989) developed a prune grading system that sorted prunes at a rate of 20 prunes/s. This system found discontinuities in intensity levels and correctly classified 95% of the prunes into three grades. Elster and Goodrum (1989) developed a system for inspecting eggs for cracks. And, Sardis and Brandin (1979) developed a system to inspect steel for surface defects at a feed rate of 10 cm/s.

For many computer vision applications, a typical video camera can be used. Through optical filters and image sensors, the video camera senses the scene information in RGB (red, green, blue) color space. Then, the camera converts the RGB information to gray

scale (Y) and chrominance (I and Q) signals. The most common output of a video camera is the National Television Systems Committees' (NTSC) composite color video signal. In this system, the gray scale signal and the chrominance signals are transmitted on one line. The in-phase portion (I), and the quadrature or 90° phase shifted portion (Q), form the chrominance signals (C) (Benson, 1986).

S - video, a newer method to transmit video information from a camera or video tape player, is gaining popularity for its improved clarity and low cost (Hirota, 1990). Hi8 and S-VHS video formats used by high end video tapes, cameras, and video players implement the S - video system. Essentially, this system operates in a similar manner to NTSC composite video transmission but the gray scale signal is transmitted on a separate line from the chrominance signals. This allows the gray scale signal to be transmitted in a wider band than on NTSC composite video, 2.0 MHz compared with 1.2 MHz for an NTSC system (Alldrin, 1994). This results in greater image resolution since the gray scale information carries most of the image detail. S - video signals typically have a resolution of 400 lines compared with 240 for an NTSC format image. The chrominance signals in an S - video system could be carried in a wider band than with an NTSC system. However, since they don't contribute to image detail, these signals are carried at the same frequencies as in an NTSC system (Alldrin, 1994). Gray scale and chrominance information is recorded separately on tape in both S - video and NTSC systems. However, with S - video systems, there is no need for electronics to combine the gray scale and chrominance signals once read from tape. As a result, the separate gray scale and chrominance lines (Y/C lines) eliminate cross-luminance and cross-chrominance interference resulting in higher signal to noise ratios than with NTSC composite video (Hirota, 1990). The image quality from an S - video system is so high that some television networks are now using Hi8 format video for recording in the field (Alldrin, 1994).

Line scan cameras are commonly used when objects are in motion or high resolution is important (Zuech, 1988). Line scan cameras produce a linear array, or an image that is one pixel wide by several pixels long. Often, line scan cameras produce images 1 by 1024 or 4096 pixels wide but cameras containing a linear array with 8192 pixels are available. As an object is passed by a line scan camera, the vision system cycles at a high rate, capturing several "line" images of the object. If the cycle rate is high enough, an image of the object can be created when all of the scans are combined in sequential order. Often, it is not necessary to cycle at a rate so that the entire surface of the object is

observed. Satisfactory results can be achieved if gaps on the object are left unobserved and the scan cycles at rates only fast enough to get a good sample of the object. To date, there is only limited availability of color line scan cameras.

The output of most cameras, whether it be a video camera or a line scan camera, is analog. Thus, for a computer to process the camera's output signal, the data must be digitized. For a video camera signal, this process is often done on an interfacing board called a frame grabber. A typical frame grabber board will input the NTSC composite or S - video signals, decode the information back to RGB format, then digitize it. Typically, the digitizing resolution will be 8 bit, or 256 levels, for each color channel. However, for many computer vision applications, 8 bit resolution for each color channel is more than adequate and computer memory can be saved by choosing a lower resolution. Humans cannot readily distinguish intensities divided up into 256 levels (Snyder, 1985). Finally, the frame grabber builds an integer array which records the RGB values for each pixel in the image and then outputs the array for processing.

For many image processing problems, one of the red, green, or blue channels of information may provide adequate information for analysis. Sometimes it is useful to convert the RGB image into a hue, saturation, and intensity (HSI) color space. Again, one or two of the HSI channels may be used exclusively in processing to save time with computations.

However, converting an image from RGB to HSI is, in itself, rather computationally intensive (Precetti, 1993). On the other hand, reducing an RGB image to a gray scale image requires fewer computations. Keil (1983) reported an accepted procedure to convert RGB images to HSI images. To convert an image from RGB to HSI, it is first converted to YIQ format. The Y portion is the gray scale information, or the intensity (I) in the HSI image. The I and Q portions are chrominance signals. Equations 4, 5, and 6 are used to convert the RGB information to YIQ format. Video cameras also use these equations to convert RGB information from their sensors to output the YIQ signal. It should be noted that the green primary color (G) most heavily influences the gray scale value (Y) because the human eye is most sensitive to the green wavelengths.

$$Y = 0.299R + 0.587G + 0.114B \quad (4)$$
$$I = 0.596R - 0.275G - 0.321B \quad (5)$$
$$Q = 0.212R - 0.523G - 0.311B \quad (6)$$

The hue and saturation values are polar coordinates of the chrominance values. To complete the conversion to HSI, the following computations need to be performed as shown in equations 7, 8, and 9:

$$\text{hue} = H = \text{Arctan}(Q/I) \quad (7)$$
$$\text{saturation} = S = (I^2 + Q^2)^{0.5} \quad (8)$$
$$\text{intensity} = I = Y \quad (9)$$

Regardless of what format the image pixels are represented, two important analysis techniques can be used: histograming and profiling. A histogram of an image is a graph of the frequency of an individual channel level (Horn, 1986). A histogram can be used to determine the levels that differentiate the background from the object. Ideally, a histogram would have two distinguishable regions, one representing the region of interest and the other region representing the rest of the image. Another important tool that can be applied is called profiling. A profile is a plot of an individual RGB or HSI level along a line in the image. This technique can be used to find discontinuities in the image gray level.

Profiles and histograms provide a method to distinguish the object of interest from the rest of the image. With the intensity or color range for the object of interest identified, the image can be converted to a binary (black and white) image. The pixels specific to the object of interest are set to dark and the rest of the image set to white. This is called applying a threshold. After thresholding, many morphological features of the object can be computed. The size of the object can be determined by simply counting pixels. Other features such as length, width, elongation, center of mass, perimeter, and orientation can easily be computed as well (Zuech, 1988 and Snyder, 1985).

There are several techniques for determining the optimum threshold level. Kittler and Illingworth (1985) review several methods for determining threshold levels. Some of the more popular methods evaluate the histogram of the intensity levels to find a threshold level at histogram peaks, modes, and centers between peaks. These are termed global

methods since they are used to determine one threshold level for the entire image. Another procedure, described by Davies (1990), uses a local method that iteratively scans the image and determines several local thresholds based on the average intensity levels within a certain distance from the pixel being evaluated. This procedure can be computationally intensive and not well suited for high speed sorting applications. However, the principle of determining a threshold level relative to neighboring pixels in an image could be useful because the features of an early split in a pistachio nut are distinguishable due to the split's relative contrast with the rest of the nut.

The common threshold methods discussed in the literature are designed for generic image processing problems and don't lend themselves particularly well for this specific early split detection problem. An ideal histogram for a pistachio nut would have two or three peaks, one for the background, one for the nut, and one smaller peak for a split, if present. The ideal threshold limit would lie between the nut peak and split peak in the histogram.

Mastin (1985) describes several filtering methods to remove small conglomerates of pixels that would be considered noise. A common method is median filtering, which examines all pixels in an eight connected (or larger) neighborhood and replaces the center pixel with the median of the neighborhood. Similarly, mean filtering replaces the center pixel with the mean of the neighborhood. However, median filtering tends to do a better job of removing extreme intensity values.

Computer vision will be implemented more frequently in the near future as computers become more powerful. Some simple color sorting machines are now only limited by the mechanical air reject mechanism which have maximum speeds of about 700 Hz (Berlage, 1984). The prune sorter developed by Tang (1989) used three 80286 based computers to process inputs from three line scan cameras (1 by 128 pixels each). This system computed the profile across the prune and rejected the prune if the profile slope exceeded a certain threshold.

For more complicated image processing tasks, personal computers generally are not powerful enough to perform all of the computations in real time. Hussain (1991) gives a lengthy description of pipelined processing that allows the frame grabbing, filtering, histograming, analysis, and decision making to be performed in sequential order. At any

one time, several images are being processed at different locations in the pipe. These systems are hardware based and are very fast, but they are also very expensive.

Handling and Orienting Pistachio Nuts

In a processing plant, pistachio nuts are conveyed by belt or pneumatic conveyors. They are single filed and dropped through color sorters with the use of vibratory conveyors. There is no work published concerning conveyance methods specifically for pistachio nuts, however, Harmond et al. (1968) describes the processes used generally for nuts and seeds of all types. Schertz and Hazen (1965) modeled and tested the movement of shelled corn on a vibratory conveyor, however, the conveyor did nothing to orient the corn.

The problem of orienting and presenting products in a consistent manner for a computer vision system can be a complicated feat and often is the limiting factor for product throughput. Mohsenin (1986), reports that an object, falling in air with velocities creating full turbulent flow, will assume the position of greatest resistance. The suture plane of a pistachio nut is nearly always the widest part of the nut. Thus, a pistachio nut falling in air or floating in a vertically upward airstream would assume a position with its suture plane horizontal. This principle has been used to orient and convey many light objects in industrial environments. Ingraham and Pearson (1993) developed a conveyor that works similarly to an "air hockey" table. The conveyor is essentially an air duct with the top surface perforated with orifices to let air escape from the plenum and slightly lift the object to be conveyed. The perforations on the top surface, however, are louvered so that the air escaping the duct also has a horizontal component to push the objects downstream. This method of conveyance is successfully being used to convey small boxes, aluminum and steel beverage cans, and some food products such as Hershey Kisses. The Kisses can be conveyed and single filed at a rate of 2000 Kisses per minute. The airstream from the orifices naturally orients the Kiss so that the pointed side is up and the large flat side of the Kiss is down, next to the conveyor surface. This type of conveyance provides a high product throughput. However, the velocity distribution of the product flow is not steady, portions of the product may accelerate to high horizontal velocities. This results in product damage due to collisions.

Thompson (1992) reports that conditions in trailer bins used to transport pistachio nuts from the orchard to the processing plant can cause staining on the nut shells in as little as

eight hours. This stresses the importance to deliver the nuts from the orchard to the processing plant as fast as possible. Also, it indicates that shell staining characteristics of pistachio nuts, like peanuts, may not be a reliable method for sorting aflatoxin contaminated nuts.

3. METHODS AND MATERIALS

Physical Properties

During the 1992 season, pistachio nuts were collected at three different orchards in the San Joaquin Valley during commercial harvest. Each of the orchards was harvested on a different date. The first orchard, near Madera, was harvested at the beginning (9-4-92), the second orchard, near Chowchilla, in the middle (9-22-92), and the third orchard, near Merced, late (9-30-92) in the harvest season. The trees in all three pistachio orchards were of the Kerman cultivar, and 1992 was a high yield year for pistachios in this area. Nuts were collected by walking down random rows in the orchard and searching all sides of each tree for early and growth split nuts. Non split nuts were also collected randomly from trees while searching for early and growth split nuts. No ladders were used so all nuts collected from trees were no higher than three meters above ground. There did not appear to be any spatial pattern of occurrence of early split nuts. The quantity of early split nuts varied from tree to tree and orchard to orchard. Many trees had no early split nuts while some trees had as many as a dozen. There did not appear to be a tendency for early split nuts to occur on a particular location on the tree, i.e. north, south, east, or west or height on the tree. Nor, did there appear to be a tendency for early split nuts to occur on a shaded florescence versus a florescence receiving full sunlight. These observations are consistent with Sommer et al. (1986). Nut samples were also taken from the harvester bins. Nuts were scooped out of the harvester bins and sorted by hand into split type groups. About 30% of the samples were from harvester bins and the remaining 70% were collected directly from the trees.

After the nuts were collected, they were placed in bulk in large polyethylene bags and kept on ice until the sample collection was completed for the day (no more than four hours). After all the nuts were collected, they were individually placed in 5.08 cm by 7.62 cm (2" X 3") zipper sealed polyethylene pouches, then placed back in the large polyethylene bag in the ice chest. Upon returning to the laboratory, 60 nuts of each split type group (early split, non split, and growth split) were randomly selected for physical property measurement. The physical properties investigated are listed in table 3.1. Nuts with shriveled appearing hulls and very small nuts (less than 10 mm in length) were not included in these tests. If one of these nuts was selected, it was set aside and a replacement was selected. Next, wet mass was measured on the 60 selected nuts from

each split type group. The nuts were returned to their individual zipper locked pouches and placed in a refrigerator kept at 4°C overnight and between all subsequent tests.

Table 3.1. Investigated properties of pistachio nuts

UNHULLED NUTS	HULLED NUTS
length	length
width	width
height	height
mass	mass
volume	hull moisture content
density	shell & kernel moisture content
moisture content	hull thickness
terminal velocity	width of split in shell
hull split length*	distance from hull to kernel
hull split width*	shell color (dried nuts)
mass center	
hull adhesion	
hull friction factor	

* early splits only

The mass of the nut was measured on an electronic scale (Sartonius, A200S). The length, width, and height of the nuts were measured with digital electronic vernier calipers (Mitutyo, 500-351). The length was defined as the distance from the calyx end to the stem (see figure 3.1). These measurements were made on all of the selected unhulled nuts. The nuts were then equally divided into two groups for further measurement. One group would remain unhulled and the other would be hulled. The nuts in the unhulled group were used to measure mass center, density, and unhulled nut moisture content. Nuts in the hulled group were used to measure hull friction factor, length and width of the hull split (early splits only), hull thickness, hull moisture content, and hulled nut moisture content.

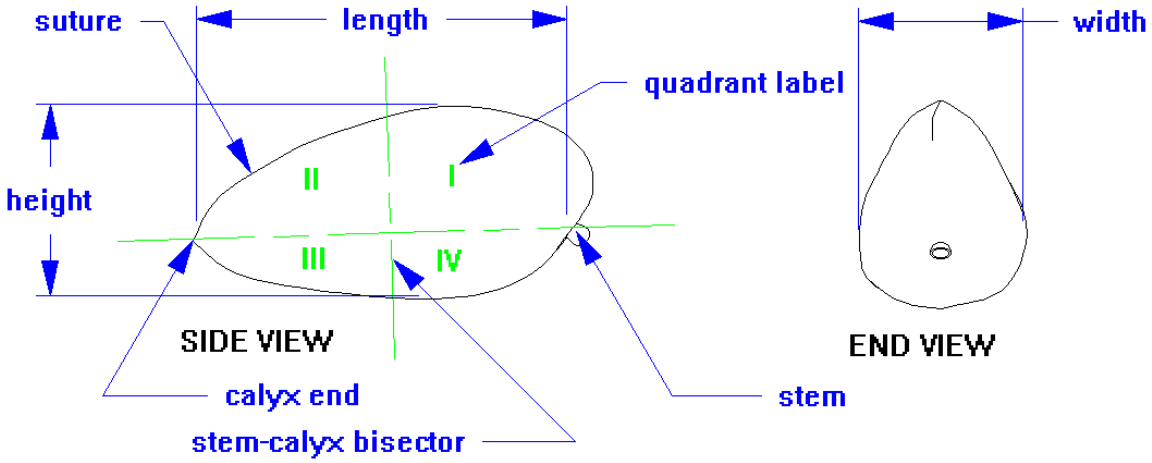

Figure 3.1. Nut Dimensions

The hull friction factor was measured using a V shaped polished stainless steel inclined trough apparatus. The nut was placed in the trough and the trough was inclined until the nut started to slide. The angle of inclination of the trough with the horizontal was recorded and the coefficient of static friction factor was calculated using the trough angle. The length of the hull split (early splits only) was measured using a ruler. The split region of the nut was rolled over the ruler to measure the "unfolded" transposed length of the split. The width of the hull split was measured at its widest point with digital electronic calipers. The nuts were hulled by hand and the wet hull mass and wet hulled nut mass (shell and kernel mass) were measured within minutes after hulling, before any drying could take place. The shell length, width, height, and hull thickness were measured with digital electronic calipers. The hull thickness measurement was taken with electronic calipers at the calyx tip.

With the dimensional measurements complete, the hulls and hulled nuts were placed in individual aluminum dishes for drying. Drying was performed in a forced draft oven (Precision Scientific, model 18) at 100°C for 12 hours, then the nuts were removed for mass measurement, and returned to the oven. Four hours later, the nuts were removed and the mass was measured again. This process was repeated until there was less than one percent change in mass from the previous measurement. For all of the experiments, the nuts consistently dried in twenty hours. The moisture content of the nuts and hulls was calculated on a wet basis.

The mass center in the suture plane of unhulled nuts was approximated by hanging the nut from a needle inserted underneath the hull skin at a point on the suture. The nut was fastened loosely enough to the needle so it could easily pivot on the needle point. With the nut still on the needle, a vertical line was drawn on the nut down from the needle point. This was repeated using another point on the suture with the nut rotated approximately ninety degrees from the previous test. The intersection of the lines approximates the mass center location in the suture plane. The nut was divided into four quadrants bordered by a line from the calyx tip to the stem intersected at its midpoint by a normal line. The quadrant (as labeled in figure 3.1, side view) containing the mass center and the distance from the calyx-stem line midpoint were recorded.

The volume and density of the unhulled nuts were measured using the pycnometer method (Mohsenin, 1986). This procedure was performed with toluene, a specific gravity flask (Fisher Scientific, 1620-25) and an electronic scale. The density of the nut was calculated using the wet mass of the nut measured the evening the nut was collected. Toluene was used for its tendency not to be absorbed by the kernel, low surface tension, low solvent action on the kernel fats and oils, and low specific gravity (Mohsenin, 1984)

The moisture content of individual unhulled nuts was measured using the same protocol as that performed with the hulls and hulled nuts. The unhulled nuts also dried to a constant mass after 20 hours. The difference in mass from the day of collection was used to calculate the moisture content on a wet basis.

The terminal velocity of unhulled nuts was measured by dropping individual nuts from a 661.66 cm (21.708 feet) height and recording drop times. Nuts were dropped from a photo sensor (Keyance, PG-602) onto a plate instrumented with an accelerometer (Dytran, 3100-A1). The time between the signals from the photo sensor and accelerometer were measured with a digital oscilloscope (Tektronix, 2430A). Using the measured drop distance and drop time, the terminal velocity was determined by iterative application of equation 10, below (Mohsenin, 1986):

$$s = \frac{V_t^2}{g} \ln\left[\cosh\left(\frac{g}{V_t} t\right)\right] \qquad (10)$$

where:
s = distance of drop (m),
g = gravitational acceleration = 9.81 m/s^2,
V_t = terminal velocity (m/s), and
t = drop time (s),

The distance from hull exterior to the kernel was measured at the calyx end of the nut. The nut was supported on end with the calyx end pointing up and the height was measured with a micrometer (Starrett, 445). The hull at the calyx end was then peeled away and the height to the tip of the kernel was measured. The difference between the two measured heights is the distance from the hull to kernel.

The shell color was measured both quantitatively and qualitatively. Early split nuts tend to have a dark brown stain on their shells along the perimeter of the split. They also tend to have a more yellowish hue all over their shell. The dried nuts from the moisture content tests were examined for a dark brown stain adjacent to the shell split or anywhere on the shell or for yellowish shell hue covering at least 90% of the shell surface. An estimate of the percent coverage of a dark brown or black stain on the shell was also made. A stain was defined as any dark brown or black discoloration of at least 2 mm in diameter. Along with these observations, the length, width, and height of the dried nuts were measured. Also, the shell color was measured with a tristimulus colorimeter (Hunter Lab, 025-A) on a 3 mm diameter spot at the apex of the shell split. This point often had a portion of the characteristic early split stain, but not always.

The hull adhesion to the shell was quantified by placing 30 nuts of a particular split type in a tumbler rotating at 43 RPM. The tumbler body was constructed from a 40 cm diameter PVC pipe and the inside lined with eighteen 1.752 cm steel angle irons for vanes (see figure 3.2). The tumbler was stopped every thirty seconds and the quantity of nuts that had been separated from their hulls was recorded. This was repeated until all of the nuts became separated from their hulls. A nut was considered separated from its hull when more than 50% of the hull became completely detached. This experiment was repeated for the 1993 harvest season with more nut samples. The 1993 experiment is discussed under the hulling properties section (page 36).

Nuts were immersed in 1% and 10% solutions of FD & C red dye number 40 (Warner Jenkinson Company, 07700). It was hypothesized that the dye would enter through the

early split lesion of the hull and stain the nut shell while normal nuts remained unstained. However, on normal nuts, the hull tends to loosely enclose the shell and dye can enter through the stem location and easily stain the whole nut. When a nut falls off the tree, the hull will often tear at the stem. Dye enters through growth split lesions as well. After 1s, immersions of 30 nuts of each split type from the first harvest, it was found that half of all of the nuts were stained. Two second and 10s immersions were performed as well, however no significant change in the amount of staining was observed with these tests. The normal nuts actually tended to be stained more thoroughly than the early split nuts. This test was not performed on the other two harvests.

Another mechanical separation method consisted of a stationary roller and a rotating roller with needles emanating from its surface (see figure 3.3). The principle of this method is that the needles on the roller will enter the lesion on the hull of an early split nut and carry it out while non split nuts would have no crevice for a needle to enter and remove the nut. Thirty nuts of each split type were placed on the rollers and its removal or retention was noted.

To present the nuts for a computer vision system, two devices were developed. The first device, shown in figure 3.4, operates by blowing air upward, lifting the nut and orienting it so that the suture plane is horizontal. The air coming out of the air duct has a small horizontal component parallel to the vee trough which conveys the nut. This device was constructed with a fan (Dayton, E37403 - 1030 RPM) and a 30.5 cm long duct made from plywood. The inside dimensions of the duct were the same as that of the fan outlet, 15.6 cm by 14 cm. The vee trough was made from 12 gauge mild steel.

The second device implements a vibrating vee to orient and convey the nuts. This was constructed by modifying a seed length sorter (Sortex, L1376). When a nut is dropped into the vee, the vibrations convey the nut and orient it so that the suture is centered in the vee and the calyx end points down as shown in figure 3.5. The seed length sorter was assembled with 1, 2, and 3 springs to resist the electro-magnet's force. It was found that the nuts were best oriented and conveyed with the three spring assembly. The driving current for the electro-magnets cycled at 60 Hz. An accelerometer was mounted to the vibrating vee assembly to determine the vibrational frequency of the vee. With the accelerometer connected to an oscilloscope (Tektronix, 305), the frequency of the vibrating vee was found to be 62 Hz with the three spring assembly. Thirty nuts of each

split type and from each harvest were placed into each device and it was noted if the nut oriented as shown in figures 3.4 and 3.5.

On September 14 and 15, 1992, nuts were sampled from two orchards near Madera, California and classified as early split, non split, growth split or hulled. In one orchard, the nuts were shaken onto a collector (canopy) and conveyed to a cubic shaped wood bin, approximately 1m by 1m by 1m in size. The wood bin would then be taken from the harvester by a forklift to a larger truck for transport to the processing plant.

In the other orchard, nuts were conveyed from the collector (canopy) to a bulk field trailer pulled behind the harvester. Augers were used to disperse the nuts in the trailer as well as to transfer the nuts to the highway transport trailers. These augers had a noticeable tendency to remove the hulls of harvested nuts.

Nuts were sampled from the collector immediately after the tree was shaken, and from either the wood field storage bin or the field trailer, depending on the system being used. In orchards where the bins were used, 1451 nuts were sampled from the collector and 2257

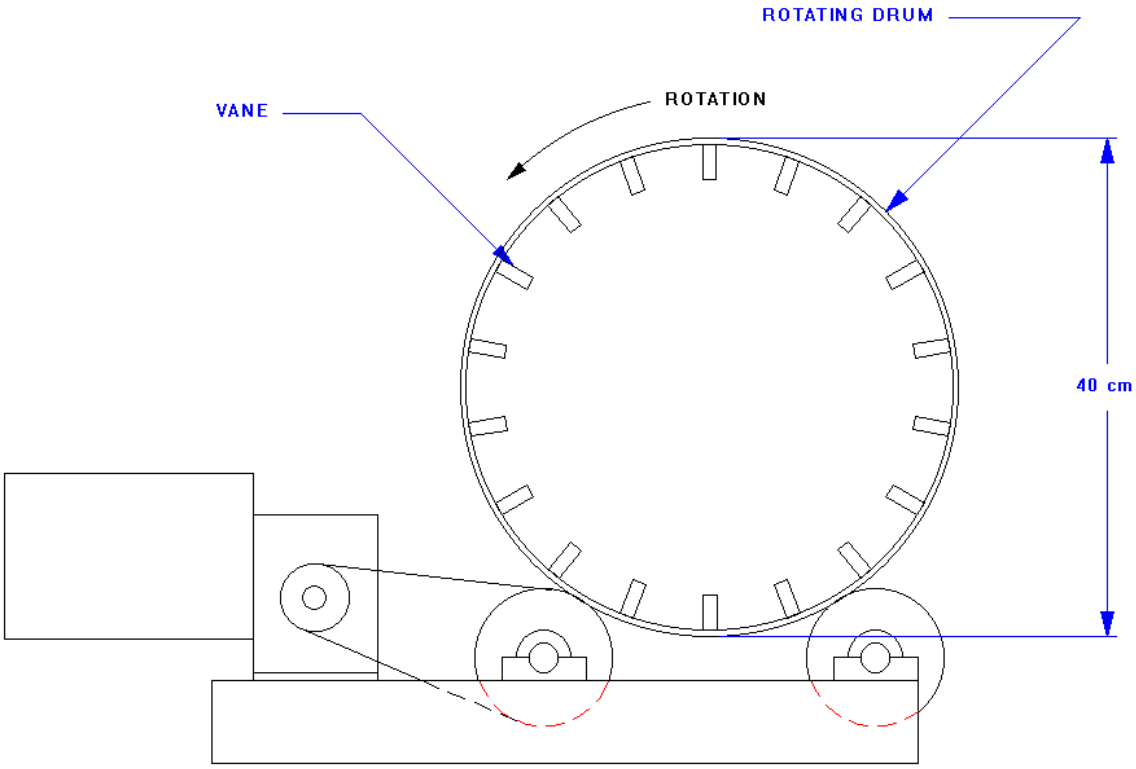

Figure 3.2. Tumbler

(image not available)

Figure 3.3. Roller and Needle Mechanical Separator

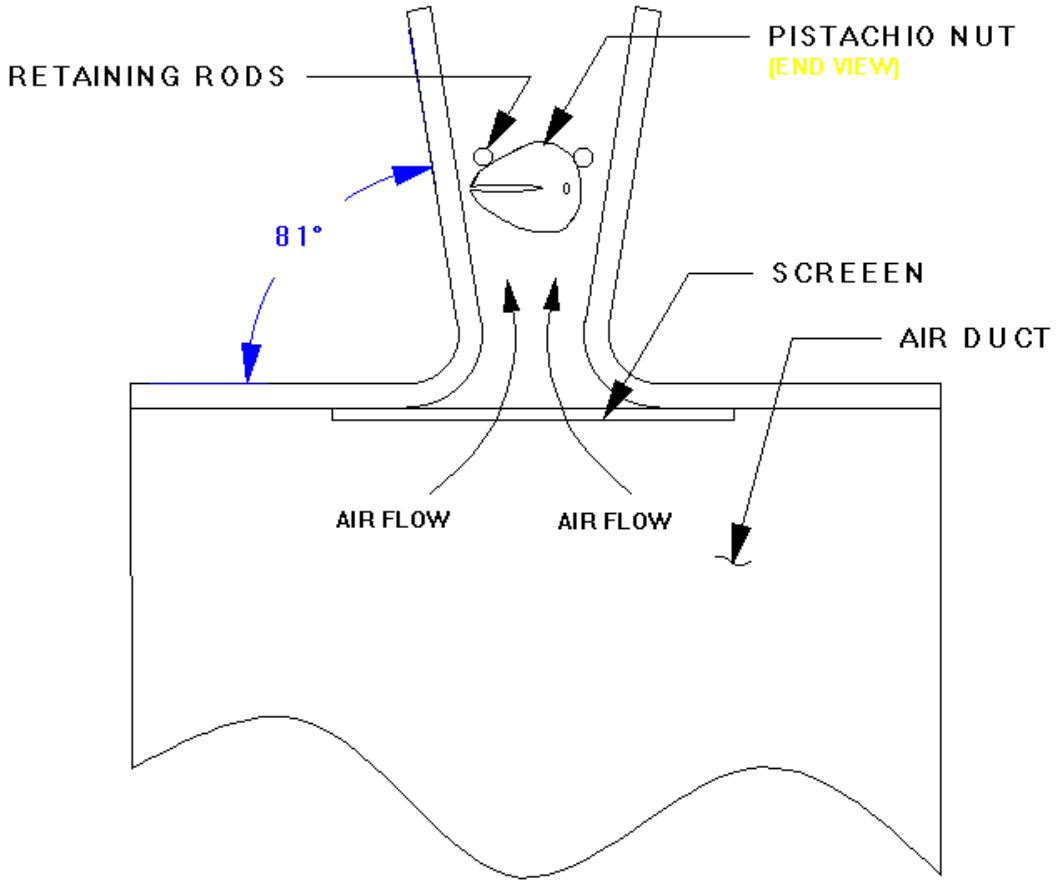

Figure 3.4. Pneumatic orienter - conveyor

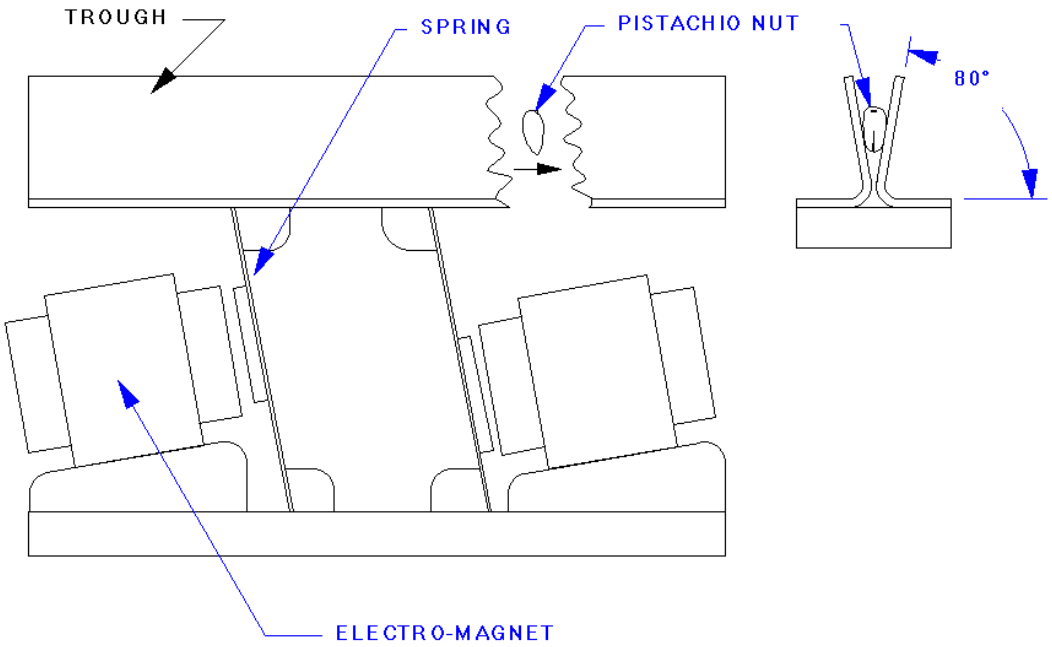

Figure 3.5. Vibrating Vee orienter - conveyor

nuts were taken from 10 different wood bins. In orchards where the field trailers were being used, 1780 nuts were sampled from the collector and 1358 nuts were taken from the trailer. In both of the orchards, nuts from the collector were sampled from three different locations in orchard. Nuts collected from the trailer were sampled from five different parts of the orchard.

Computer Vision

a) Equipment and Image Preperation

Twenty color images from each orchard and split type were taken the day after collection. The images were taken with a Yashica video camera (KD-H170U) and recorded on Sony Hi8 Metal-E video tape. The images were digitized with an Apple Macintosh fx computer equipped with a RasterOps frame grabber (24XLTV). The RasterOps frame grabber had a built in S - video (Y/C) decoder. S - video signals were input to the frame grabber by using the video camera as an S - video tape player. The images were digitized into 640 x 480 color image files with 256 intensity levels for each primary color (RGB) and stored in PICT format to conserve storage media space. All of the images were taken with the pistachio nut centered under a fluorescent light ring 8" in diameter and the camera looking through the ring. The orientation of the pistachios in all images was such that the suture was centered on the nut and facing the camera with the suture oriented parallel to the rows in the image. With this type of orientation, the suture and an early split lesion, if it exists, would also be expected to be centered in the image and aligned with the rows of the image. A white background was used and the nuts were presented with their suture facing upward, as shown in figure 3.6. As can be seen in figure 2.1 (page 9), the lesion in the hull that characterizes an early split pistachio nut is generally a long, narrow, dark edged region on the suture of the nut. Growth splits can also occur on the suture of the nut, but they tend to be wider and not as dark as an early split lesion. In addition, a growth split very rarely would both lie directly on the nut's suture and be parallel with the long axis of the nut as is always true of an early split lesion. A software package (Adobe Photoshop 2.5) was used to crop images from 640 X 480 pixel images to 256 X 256 images and convert the files from PICT files to TIFF format for processing. The images were then loaded onto a Sun Sparc workstation (model ipx, 40 MHz) for analysis.

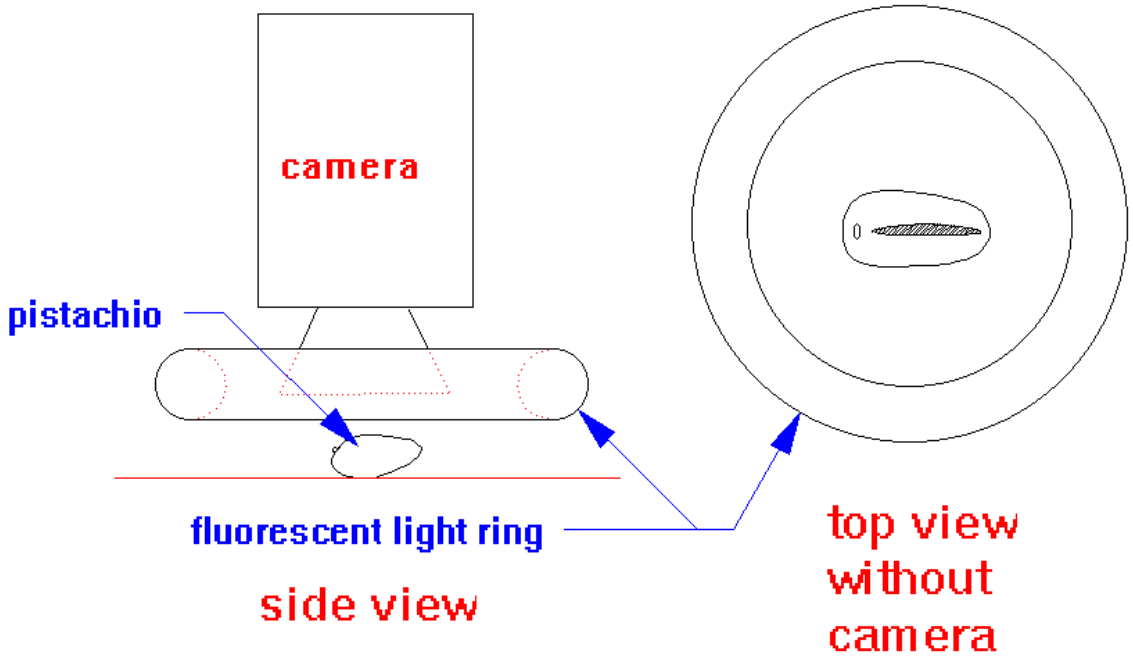

Figure 3.6. Pistachio lighting and camera set up

In the Sun workstation, the images were converted to ASCII files, and converted from RGB images into gray scale. Only gray scale images were used extensively in image processing since there was no noticeable difference in color between early split and normal nuts. Equation 11 was used to convert the RGB values to gray scale (Y).

$$Y = 0.299R + 0.587G + 0.114B \qquad (11)$$

b) Thresholding Pistachio Nut Images

Since the dark early split lesion would always appear in the image, it was thought that nuts could be classified by intensity information only. Eight bin gray level histograms were computed for each nut (intensity increments of 0 to 31, 32 to 63, 64 to 95, ...224 to 255). After discriminate analysis (SAS, 1989) was performed on this data, it was found that 96.5% of the non split nuts, 83% of the growth split nuts, and 81% of the early split nuts were correctly classified. These results were not considered adequate so this method was not pursued further.

After examining histograms of 10 nuts of each split type, it was observed that no single threshold could be set to isolate all of the early splits in the nut population. Thresholds of

20, 30, 40, 50, 60, and 70 were applied to the 10 sample nuts. While one of the threshold levels would isolate the early split on an individual nut, there was no one threshold level that would work for all of the nuts.

While attempting to find one threshold level for all of the nuts, it was observed that most of the darkest pixels on early split nuts were contained in the split region of the nuts. With this observation, it became apparent that an early split could be isolated by determining a threshold based on a level that would convert a set percentage of the lightest pixels from the image to the background. Figure 3.7 shows an early split nut, histogram, and binary images with thresholding at various levels. The term "90% threshold" for example, means that the lightest 90% of the pixels were converted to white, while the darker ten percent was converted to the black object. Thirty of the early split images were thresholded at the 90%, 95%, 97%, 98%, and 99% levels. The binary images were then evaluated for the best threshold percentage level. In all cases, the 90% and 95% levels left objects not representative of an early split. The remaining object was often wider than an early split, as can be seen in figure 3.7. The 99% threshold often eroded the split too much, so what remained was much shorter than it actually was. Moreover, the remaining image was often fragmented. The 98% threshold limit consistently gave the best representation of the split without too many other objects surviving. In all cases with the 98% threshold limit, the early split was represented clearly by a single long but narrow object. The 97% threshold limit occasionally would leave a better representation of the split than the 98% level, but more often, it would not remove other, non split objects. The 98% threshold was chosen as the best level and all of the early splits, growth splits, and non split images were thresholded at this level and saved for further evaluation.

The histograms and binary images for a typical growth split and non split nut are shown in figures 3.8 and 3.9. The darker pixels in growth split images also fall within the split region However, the region is not centered on the image and has a lower length to width ratio. On non split images, the darker pixels are either randomly scattered or are concentrated at the edge of the nut.

The problem with this method of thresholding is that no matter what type of nut is under consideration, the thresholding will leave the set percentage of pixels as objects that will need to be dealt with. For growth split nuts, the surviving 2% of the pixels could be concentrated in the split region, making it difficult to distinguish from an early split. For

both non and growth split nuts, the darkest 2% of the pixels could also be concentrated along the edge of the nut, leaving a long narrow object, not unlike an early split. Examples of these problems are shown in figure 3.10. The two growth split nuts leave objects that appear very similar to that of an early split nut. The edge of a non split nut can often appear as an early split as shown in figure 3.10.

This method isolates the early split region of pistachio nuts but it also leaves other objects in growth and non split nuts. The remaining regions in growth and non split nuts could probably be distinguished from the early split regions but this would be computationally expensive. Thus, this method was not investigated further.

(image not available)

Figure 3.7. Early split nut image thresholding

(image not available)

Figure 3.8. Non split nut image thresholding

(image not available)

Figure 3.9. Growth split nut image thresholding

(image not available)

Figure 3.10. Problems with thresholding

c) Intensity Profiles of Pistachio Images

Intensity profiles of the nut were computed on every fourth column in the nut image. This spacing represented approximately 0.5 mm on the nut. Examples of typical profiles for non split, growth split and early split nuts are shown in figure 3.11 (Note: the images have been rotated 90° for illustration purposes).

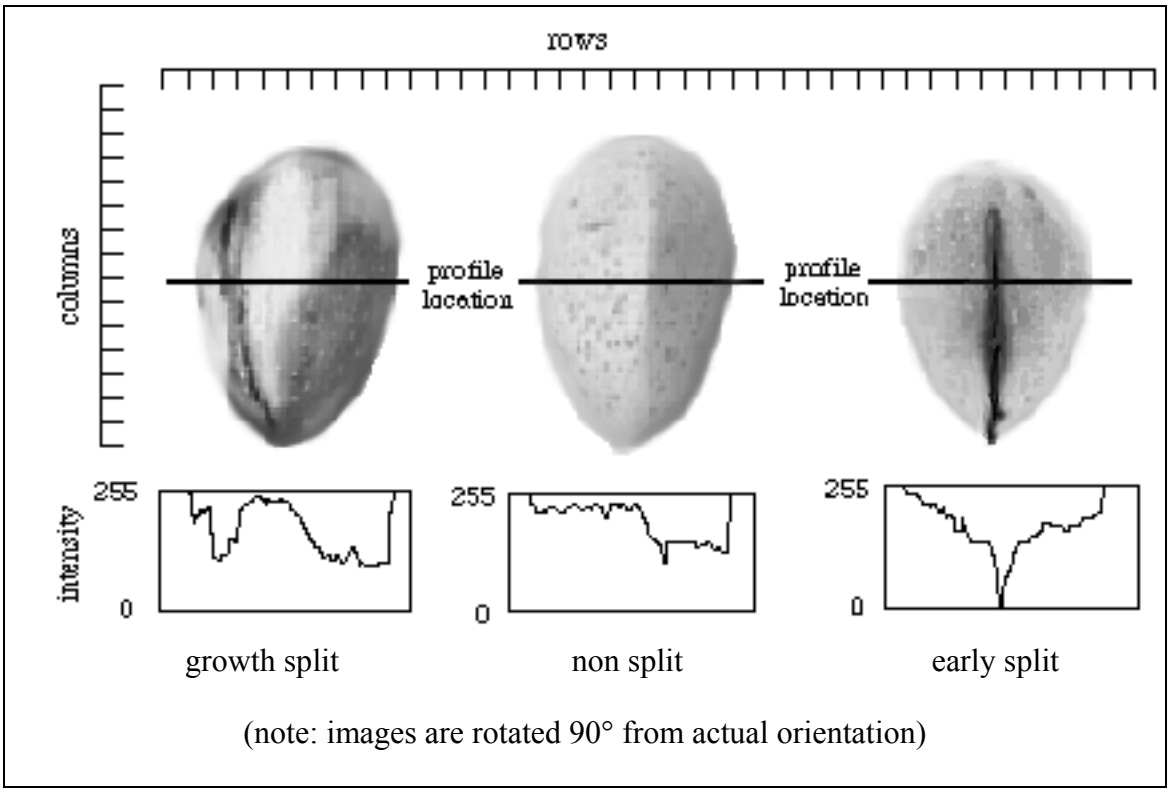

Figure 3.11. Typical pistachio nuts and profiles

If the profile crosses an early split lesion, then the profile minimum intensity will be significantly less than the profile mean intensity. For each profile examined, the profile mean and the mean of a 7 pixel segment centered about the minimum intensity pixel was computed. If the profile minimum was located within 13 pixels of the profile center and the mean of the 7 pixel segment was less than 60% of the profile mean intensity, then this profile was considered likely to be crossing an early split. The maximum number of consecutive adjacent profiles meeting this criteria was computed for each nut. Based on this criteria alone, a high classification accuracy can be achieved. Of the 60 early split nuts examined, 58 had at least 10 adjacent profiles that met the above criteria while none of the non split nuts did and only 2 of the growth split nuts did.

The nut center was computed by scanning the columns, from top to bottom, of the image where profiles were to be computed. The image background was set to white (255 intensity) to ease detection of the nut region in the image. This was done because many of the nut images had shadows that made the nut look larger than it actually was. If the light source was more diffuse, then shadows would have not been a problem.

The top edge of the nut was detected when the intensity level dropped below 255 for at least two consecutive rows and the pixel ten rows above was 255. This reduced the chance of false edge detection caused by noise. Similarly, the bottom edge of the nut was detected when the image intensity returned back to white (255 intensity). The width of the nut was computed by subtracting the top edge row number from the bottom edge row number. The location of the center of the nut for a particular column was computed by adding the top edge row number to half of the nut width. This simple algorithm works very well if the nut is well oriented and is forgiving if the long axis of the nut is skewed. In appendix C, the orientation of the examined nuts are shown. The image data from the skewed nuts was not significantly different from what would be expected if the nut was well oriented.

The combination of a 13 pixel maximum difference from profile minimum to nut center and a 7 pixel segment mean less than 60% of the overall profile mean yielded the most accurate classifications of early split nuts. Other combinations were investigated. As discussed earlier, the mean of a 7 pixel wide segment centered on the minimum of the profile mean, was computed. Segments of 3, 7, and 11 pixels centered on the profile minimum were also tested, but 7 pixels achieved the best classification accuracy. Distances of 8, 10, 13, 15, 19, and 21 pixels from the profile minimum to the nut's centerline were examined. And, segment mean intensity percentages of 40%, 60% and 80% of overall profile mean intensities were tested.

Finally, the intensity level of the split region of each nut was compared to the whole nut intensity level. The profiles that were members of the group of maximum consecutive profiles that met the early split criteria were re-examined by computing the mean of all of the 7 pixel segments centered on the minimum of each profile. If an early split was being examined, this would be an approximation of the mean intensity of the split region; this region is much darker than the rest of the nut. If a growth split nut with its split near the suture is being examined, the mean of the split region will also be computed; but growth

split lesions do not tend to be as dark as early splits. This data can be used to further enhance classification between early split nuts and growth splits. Also, with growth split nuts, some shell can be seen through the lesion. This makes the average intensity of the growth split region even lighter.

With the average intensity of the split region computed, the nut image was examined once again. A ratio of pixels with intensities less than the split region mean and pixels greater than the split region mean was computed. On early split nuts, the darkest pixels normally occur in the split area and this ratio is small. However, on non split and growth split nuts, this ratio of pixels is larger because the difference between the computed mean and the expected intensity of any other pixel on the nut is not as great. A ratio of intensity values is needed to normalize lighting fluctuations and variances in overall nut color differences.

The program used to perform this analysis was written in C and is listed in appendix A. The program to convert the image from TIFF RGB format to ASCII gray scale format is in appendix B. Illustrations of the nut images are shown in appendix C.

Hulling Properties

During the 1993 harvest season, 5 orchards were sampled. The first orchard, located near Hamilton City, was sampled on September 7. The second orchard, near Madera, was sampled on September 13. The third orchard, near Arbuckle, was sampled on September 20. The fourth orchard, near Chowchilla, was sampled on September 27, and the fifth orchard, near Merced, was sampled on October 3. The orchards near Madera, Chowchilla, and Merced were the same orchards used during the 1992 harvest. The Hamilton City and Arbuckle orchards are in the Sacramento Valley, about 200 miles north of the other three orchards. The year 1993 was a "light" year for pistachio production in their biennial cycle.

On August 7, sixty early split nuts in each of the Madera, Chowchilla, and Merced orchards were tagged with a bright purple ribbon. When the orchards were sampled at harvest time, each of the tagged nuts was collected and examined for hull shrivel. Also, approximately 150 non-tagged early split, growth split, non split and shriveled early splits were collected. The nuts were separated into split types and placed in bulk in quart

sized zip lock polyethylene bags. The bags of nuts were then placed in a gallon size polyethylene zip lock bag, then placed in an ice chest for transport back to the laboratory.

The next day, thirty nuts of each split type (including shriveled early split nuts) were randomly selected and weighed. The non split, growth split and early split nuts were hulled and all of the nuts were placed in water. It was noted if a nut floated or not. After hulling, if a nut shell was found to be unsplit, the nut was removed from the test. A replacement nut was randomly selected, weighed, and hulled. Unsplit nuts often do not have developed kernels and float on water. Since the hulls of shriveled nuts adhere very tightly to their shells, these nuts often are not hulled in commercial hullers. Shriveled and tagged early split nuts were not hulled before placing in water. If the nut floated, it was noted. This was done to see if unhulled shriveled nuts could be separated from other hulled nuts by floating in water after a differential hulling treatment.

Next, sixty nuts were randomly selected and the time required for hulling in the tumbler was recorded. Twenty nuts at a time were placed in the tumbler. The same procedure as in 1992 was used to record the hulling times in the tumbler.

A new device to test the hulling characteristics of pistachio nuts was made for the 1993 samples. This device consisted of a variable speed right angle drill (Makita, DA3000R) with a 16 grit 13 cm diameter sanding disk attached. Around the sanding disk was a 14 cm inside diameter aluminum pipe. Lined on the inside of the pipe was 40 grit sandpaper attached with double stick tape. Essentially, this device looked and worked like a small scale potato peeler, see figure 3.12. The nuts were placed on the spinning sanding disk and the centrifugal force threw the nuts against the inside of the pipe wall. The nuts rubbed or bounced along the inside surface of the pipe. The friction between the nut and sandpaper on the pipe and sanding disk eventually removed the hull. Only rarely was the hull worn or ground off by the sandpaper. For non split nuts, where the hull typically is loosely attached to the shell, the hulls normally sheared in half and the nut easily fell out. Growth split and non split nuts were typically hulled in 5 to 15 seconds, while early splits and shriveled early split nuts, with their hulls typically tightly attached to their shells, often could not hull in 40 seconds.

With the drill speed set at 900 RPM, 40 nuts of each split type were placed individually in the spin huller for a maximum of 40 seconds. The time for the nut to become hulled was recorded. If the nut was not hulled within 40 seconds, it was noted. A nut was

considered hulled if more than 50% of its hull was completely separated from the shell. On approximately 10% of the early split nuts, half of the hull was separated from the shell in less than 40 seconds while half of the hull remained attached for 40 seconds. These partially hulled nuts were recorded as unhulled.

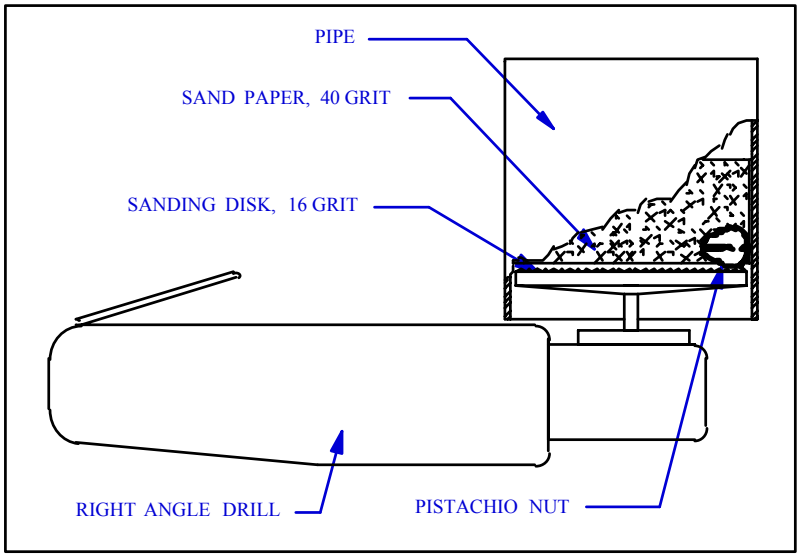

Figure 3.12. Spin huller

4. RESULTS

Physical Properties

Twenty percent of the tested non split nuts had undeveloped kernels. In addition, 9% of the growth split nuts were found to have undeveloped kernels and unsplit shells. These types of nuts are removed by conventional pistachio processing machinery. To avoid bias to the normal nut data, the measurements from these undeveloped nuts were removed from further analysis.

The first step in analyzing the data was to determine if the mean for a given property was significantly different for early splits than for non split and growth split nuts. This was performed with Fishers least significant difference test with $\alpha = 0.05$. Listed in table 4.1 are the means, minimum, maximum, coefficient of variance (CV), sample size and significance for the pistachio properties studied. The hull adhesion and needle separator tests were not included in this analysis.

The Fishers LSD test was performed as a preliminary screening to determine the most important properties to classify nuts into split types. Discriminate Analysis (SAS, 1989) was then used to evaluate the feasibility of using individual or multiple pistachio properties to differentiate early split nuts from the other nut types. Pistachio nut properties listed in table 4.1 that were not significantly different between early split and normal categories were not included in the classification study.

Discriminate models could only be made using properties of either hulled nuts or unhulled nuts as these two groups of tests used different samples. The bulk hulling and handling processes in current practice at pistachio processing plants in California cannot keep track of a nut through the huller. Thus, a model using both hulled and unhulled properties would have little practical value. The best models found for classifying nuts by split type for hulled and unhulled nuts are listed in table 4.2. The total nuts correctly classified was calculated by weighting the early split classification by 4%, non split nuts by 76%, and growth split nuts by 20%. These percentages are the estimated percentage of each split type in the pistachio population.

Table 4.1. Statistics of investigated pistachio properties

PROPERTY	EARLY SPLIT NUTS					NON SPLIT NUTS					GROWTH SPLIT NUTS					sig. diff.
	mean	min	max	cv (%)	n[1]	mean	min	max	cv (%)	n[1]	mean	min	max	cv (%)	n[1]	means[2]
UNHULLED NUTS:																
hull friction factor	0.39	0.22	0.59	18.50	180	0.34	0.18	0.49	31.91	143	0.40	0.32	0.47	9.57	173	no
hull thickness (mm)	1.31	0.25	2.60	29.85	180	1.82	0.41	2.77	25.39	143	1.62	0.27	2.21	22.79	173	yes
height (mm)	16.49	12.33	20.67	9.17	180	18.51	15.55	23.07	7.89	143	17.05	12.53	20.35	9.43	173	yes
length (mm)	21.56	13.55	26.31	6.45	180	24.22	20.66	28.35	5.87	143	21.93	14.35	26.27	8.34	173	yes
width (mm)	15.08	11.22	21.92	8.99	180	16.75	14.32	20.25	7.49	143	17.05	12.63	23.52	11.32	173	yes
mass (g)	2.72	1.26	4.43	21.75	180	3.62	1.80	5.58	19.20	143	3.22	1.99	4.65	18.78	173	yes
volume (ml)	2.60	1.21	3.83	21.58	180	3.82	2.50	5.35	16.76	143	3.13	1.94	4.50	22.32	173	yes
density (g/ml)	1.03	0.88	1.28	6.51	180	0.93	0.68	1.11	12.03	143	1.03	0.88	1.33	4.32	173	no
moisture (% w.b.)	45%	9%	60%	25	180	54%	38%	70%	10	143	48%	16%	69%	19	173	no
hull split length (mm)	26.71	15.00	60.00	29.85	180	n/a	n/a	n/a	n/a		n/a	n/a	n/a	n/a		n/a
hull split width (mm)	1.10	0.10	3.50	76.21	180	n/a	n/a	n/a	n/a		n/a	n/a	n/a	n/a		n/a
terminal velocity (m/s)	11.69	9.92	13.12	5.95	90	12.47	10.77	14.55	7.93	90	11.54	10.11	13.42	0.91	90	no
mass center[3], radius (mm)	3.80	1.00	7.00	37.18	90	3.80	1.00	7.00	41.84	90	n/a	n/a	n/a	n/a		no
HULLED NUTS:																
hull moisture (% w.b.)	77%	57%	83%	7	90	79%	66%	90%	6	52	76%	54%	85%	8	83	no
moisture (% w.b.)	41%	26%	84%	45	90	37%	29%	43%	10	52	34%	25%	43%	12	83	no
height (mm)	14.60	10.75	18.69	8.71	90	15.99	13.74	18.92	7.33	52	15.06	12.43	18.00	8.15	83	yes
length (mm)	19.31	14.89	22.48	7.91	90	20.63	13.46	24.16	7.73	52	19.85	15.77	22.95	6.62	83	yes
width (mm)	12.77	10.10	14.76	6.98	90	14.21	12.35	16.03	5.63	52	13.50	11.14	15.86	7.22	83	yes
shell split width (mm)	1.01	0.21	3.32	75.14	90	2.52	0.25	6.05	47.93	52	2.48	0.41	5.32	39.56	83	yes
mass (g)	1.85	0.81	2.64	18.06	90	2.41	1.72	3.16	12.25	52	2.11	1.26	4.10	19.42	83	yes
shell color[4] (x value)	0.403	0.349	0.444	4.30	83	0.364	0.339	0.396	3.36	88	0.373	0.343	0.426	4.80	53	yes
shell color[4] (y value)	0.381	0.349	0.407	2.87	83	0.362	0.334	0.383	2.46	88	0.371	0.332	0.408	3.70	53	yes

Notes:

1. n = Sample Size.
2. Significantly different means at the 5% level.
3. 77% of the mass centers on early split nuts fell in quadrant 1, 19% in quadrant 2, and 4% in quadrant 4. 84% of the mass centers on non split nuts fell in quadrant 1, 11% in quadrant 2, and 5% in quadrant 4. Growth split nuts were not evaluated in this experiment.
4. Chromaticity values are normalized.

Table 4.2. Classification of pistachio nuts using hulled and unhulled nut properties

CLASSIFICATION MODEL	NUTS CORRECTLY CLASSIFIED (%) Early split	Non split	Growth split	Total[1]
hulled nuts:				
shell color	81.8	96.2	84.3	93.2
length, width, shell split width	74.4	77.8	82.2	78.5
length, width, height, shell split width	74.4	76.7	80.0	77.3
length, height, shell split width	74.4	74.6	80.0	75.7
length, width, height	62.2	80.0	70.0	77.3
length, width, height, mass	61.1	92.2	73.3	87.2
unhulled nuts:				
mass*volume	92.2	74.4	65.6	73.4
length, width, height, mass, volume	90.0	87.8	54.4	81.2
mass, volume	90.0	82.2	57.8	77.6
length, width, height, mass*volume	82.2	91.1	70.0	86.5
length, width, height, mass	82.2	84.4	56.1	78.7
length, width, height, volume	81.1	88.9	70.0	84.8
mass	78.9	71.7	63.3	70.3
length, width, height	77.2	87.8	59.6	81.7
length, height	70.6	86.7	62.8	81.3
length, width	70.0	86.7	62.6	81.2
volume	64.4	95.5	64.4	88.0
density	21.1	95.6	83.3	90.2

Note:
1. The total nuts correctly classified is calculated by weighting the early split classification by 4%, the non split classification by 76% and the growth split classification by 20%.

Examining table 4.2, for unhulled nuts, the product of mass and volume classified nuts into the correct split types with the fewest early split errors. However, measuring both volume and mass for an individual nut at a high throughput rate is not an immediately feasible commercial option.

Shell color is the most distinguishable characteristic of hulled early split pistachio nuts. This classification is based on the chromaticity of the tristimulus color reading results. Inspecting the hulled nuts after the moisture content tests, 75% of early split nuts, 7% of growth split nuts and 0% of non split nuts had stains adjacent to the split edge. Also, 45% of early splits, 4% of growth splits, and 2% of non split nuts had a yellowish hue over at least 90% of their shells.

Using both the categorical shell stain data (stain adjacent to split perimeter or no stain, and yellowish hue or not) and the dimensions of the hulled and dried pistachios, nuts were classified into the split types. If a shell had a stain adjacent to the shell split, or had a yellowish hue, or if the product of its length and width was less than 230 mm^2, then it was classified as an early split. This criteria correctly classified 90% of the early splits, 97% of the non splits, and 76% of the growth split nuts. Other models using all of the dimensions were evaluated, but no improvement in classification accuracy was found. It is not known if early split nuts are more prone to yellow shell stains for the entire pistachio population. Furthermore, the yellow stain is not likely caused by *Aspergillus* molds. When the yellow stain data is removed from the classification algorithm the classification accuracy of early split nuts is reduced somewhat: 84% of the early splits, 98% of the non splits, and 83% of the growth split nuts were correctly classified.

The extent of staining on a shell does not appear to give an indication of its split type. The introduction of the percent stain coverage data into a sorting criteria reduces the sorting accuracy rather than enhancing it. However, non split nuts tend to be more heavily stained on the stem end while early split nuts tend to have more staining in the middle of the nut shell. If the hulled nuts were to be inspected with a computer vision system, this criteria could be helpful along with the other classifying criteria previously discussed.

The roller and needle device successfully removed 90% of the early split nuts and only 5% of the non split nuts. However, the roller also removed 95% of the growth split nuts. This device could be useful as a quick pre-sorter in front of a more time intensive sorter such as a computer vision system. With the mechanical pre-sorter, most non split nuts would by- pass the secondary sorting equipment.

The orientation devices performed quite well. The air orienting device correctly oriented 98% of the early split nuts, 100% of the non split nuts, and 96% of the growth split nuts. The vibrating vee correctly oriented 97% of the early split nuts, 99% of the non split nuts and 95% of the growth split nuts.

Of the 3231 nuts sampled from the harvester collectors on September 14 and 15, 1992, 87% were classified as non split, 11% were growth split, and 2% were early splits. These results confirms the study by Sommer et al. (1986) that early split nuts comprise of 2 to 4% of the pistachio harvest. No nuts from the harvester catch frame were found to be

hulled. Of the 2257 nuts collected from the wooden bins, only four (0.18%) were found to have no hulls. Of the 1358 nuts collected from the field trailers pulled by the harvesters, 23% were found to have no hulls. This data shows that many of the hulls of pistachio nuts may be removed before delivery to the processing plant if the storage trailer system was used during harvest. A sorting method to eliminate early split nuts at the processing plant would need to account for pre-hulled nuts. The storage trailer handling method is becoming more popular because, in 1992, the processing plants were paying approximately $0.02 more per pound of nuts delivered in bulk trailer loads rather than the wood field bins.

Computer Vision

Discriminate analysis (SAS, 1989) was performed on the image processing data. The parameters used in the discriminate models were: pixel intensity ratio, number of maximum adjacent profiles meeting early split criteria, and the length and width data. A summary of the classification performance using different models is listed in the table 4.3. The data for each individual nut and an image of the nut are in appendix C.

Table 4.3. SAS discriminate analysis results

	PERCENT NUTS CLASSIFIED AS EARLY SPLITS		
MODEL	**Early splits**	**Non splits**	**Growth splits**
maxP, length*width	100.0	0.0	3.3
maxP, length	100.0	0.0	6.7
maxP, width	98.3	0.0	5.0
maxP	98.3	0.0	6.7
maxP, pr, length, width	96.7	0.0	3.3
maxP, pr, length*width	95.0	0.0	3.3
maxP, pr	93.3	0.0	3.3
pr, length*width	90.0	8.3	21.7
pr	86.7	38.3	30.0

where:
maxP = maximum consecutive adjacent profiles that met the early split criteria
pr = (pixels with intensities below split region mean)/(pixels with intensities above split region mean)

Early split pistachios tend to be smaller than non split and growth split nuts. When images of the nuts were taken, their lengths and widths were also recorded. It appears that by adding the product of the length and width to the profile criteria, a high percentage of early splits can be correctly classified and the error rate for growth split nuts is enhanced. Figure 4.1 shows a plot of length and width product versus maximum adjacent profiles meeting early split criteria (maxP). Examining this graph, 59 of 60 early split nuts are found to reside in a space bounded by a length and width product less than 250 mm^2 and at least 10 adjacent profiles meeting early split criteria. Two of 60 growth split nuts and none of the 60 non split nuts are found in this space. The two growth split errors have close length - width products so only one point can be seen on figure 4.1

Hulling Properties

The tumbler tests from the 1992 harvest produced positive results. The growth split nuts required the shortest time to become separated from their hulls and non split nuts required slightly more time. Of the growth split and non split nuts, 95% became separated from their hulls in 180 and 210 seconds respectively. The early split nuts required 360 seconds for 95% of their hulls to become separated from their shells while only 2% of the early split nuts lost their hulls before 210 seconds. These results indicate that hull adhesion may be a viable classification parameter.

The 1993 hulling results indicate that differential hulling could be an attractive method to separate early splits from normal nuts. In the spin huller, 98.6% of the non split and 92.3% of the growth split nuts hulled within 20 seconds. Conversely, only 6.8% of the early splits and 1% of the shriveled early split nuts hulled within 20 seconds. After 40 seconds, 72.7% of the early split nuts and 92.7% of the shriveled early split nuts did not hull. Table 4.4 displays the cumulative results from all of the spin hulling tests, and figure 4.2 shows a graph of the hulling times for all of the nuts tested. In the tumbler, 100% the non split nuts and 97% of the growth split nuts hulled within 180 seconds.

Only 9% of the early splits and none of the shriveled early split nuts hulled within 180 seconds. After ten minutes in the tumbler, 51% of the early splits and 97% of the shriveled early split nuts remained unhulled. Table 4.5 lists the cumulative results from all of the tumbler tests, and figure 4.3 shows a graph of the hulling times for all of the nuts tested with the tumbler.

It was observed that 93% of the early split nuts tagged on August 7, 1993 were shriveled at harvest time. The remaining 7% of the early split nuts were un-shriveled despite having exposed kernels for at least a month before harvest.

The float tests showed that unhulled shriveled early split nuts tend to have lower densities than hulled non split, growth split and early split nuts. From the float test, it was observed that 90% of the hulled non split, 27% of the hulled early split and 84% of the hulled growth split nuts sunk in water while only 1.7% and 1.1% of the unhulled tagged early splits and unhulled shriveled early split nuts sank. A significant number of hulled non splits (10%) and hulled growth split nuts (16%) floated in water. This was not expected especially since care was taken to exclude nuts with unsplit shells. These results suggest that unhulled shriveled nuts can be separated by a float treatment, but that significant portions of non split and growth split nuts will be erroneously separated as well. If the floated nuts were later passed through a color sorter, the hulled non split and growth split nuts might be separated from the unhulled shriveled early split nuts. Surprisingly, 73% of the hulled early split nuts float on water. This suggests that many of the hulled early split nuts are removed by the float treatment after hulling during normal pistachio processing. The 1992 density measurements indicated that unhulled early split nuts had a specific gravity of about 1. Since the 1993 data indicates that a majority of hulled nuts float on water, the density of the hulls on early split nuts may be greater than the shell and kernel density. The hulls for normal nuts do tend to be thicker and have a "spongy" feel to them compared with the relatively thin early split hull.

Table 4.4. Time required for hulling in spin huller

TIME REQUIRED FOR HULLING (S)	CUMULATIVE PERCENTAGE OF NUTS HULLED IN SPIN HULLER			
	Non split nuts	Growth split nuts	Early split nuts	Shriveled early split nuts
4	7	10	0	0
8	37	45	1	0
12	74	74	4	1
16	92	84	6	1
20	99	91	7	1
24	99	95	12	2
28	99	95	14	2
32	100	96	18	5
36	100	98	23	6
40	100	100	27	7

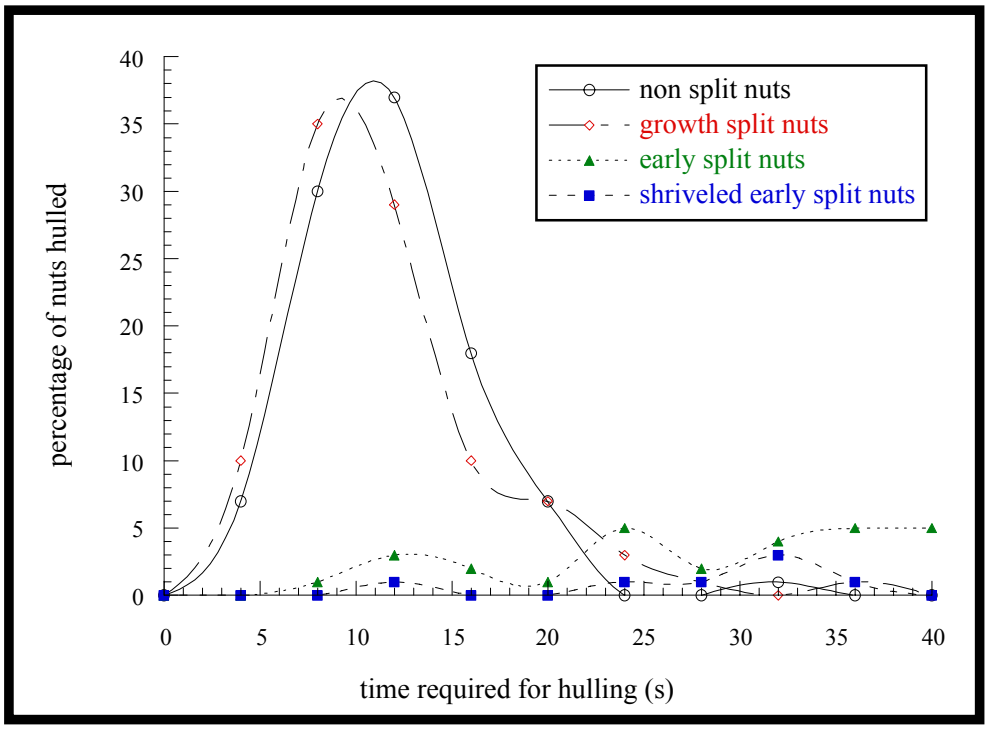

Figure 4.2. Graph of percent nuts hulled versus time in spin huller

Table 4.5. Time required for hulling in tumbler

TIME REQUIRED FOR HULLING (S)	CUMULATIVE PERCENTAGE OF NUTS HULLED IN TUMBLER			
	Non split nuts	Growth split nuts	Early split nuts	Shriveled early split nuts
30	18	36	1	0
60	66	77	2	0
90	89	90	3	0
120	98	94	4	0
150	99	96	7	0
180	100	97	9	0
210	100	98	11	0
240	100	100	14	0
270	100	100	18	0
300	100	100	22	1
330	100	100	29	1

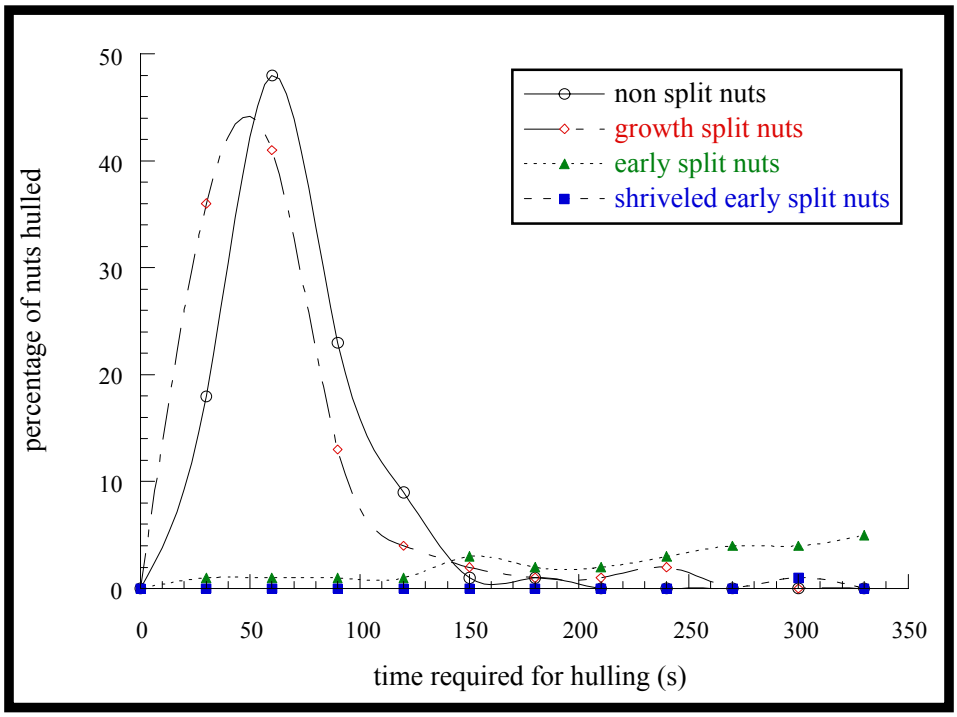

Figure 4.3. Graph of percent nuts hulled versus time in tumbler

The nut mass data collected from the 1993 samples indicates that early split nuts are generally lighter than non split and growth split nuts confirming observations from the 1992 study. The shriveled and tagged early split nuts are significantly lighter than normal nuts. However, early split nuts cannot be separated on the basis of mass alone. Of the early split nuts, 25% had a mass of at least 3.53 g, while 25% of the non split nuts had a mass of less than 3.47 g. This shows that there is a large overlap with the distributions of the non split and early split nut masses. However, all of the shriveled early split and 99% of the tagged early split nuts weighed less than 2.91 g. while 95% of the non split nuts and 90% of the growth split nuts weighed more than 2.91 g. This indicates that shriveled early split nuts could be separated from normal nuts based on mass alone. The results from the 1993 nut mass measurements are shown in table 4.6.

Table 4.6. Results of mass measurements of hulled pistachio nuts collected in 1993

	MASS STATISTICS OF PISTACHIO NUTS			
NUT SPLIT TYPE	**Mean (g)**	**Maximum (g)**	**Minimum (g)**	**Coefficient of variance**
non	3.85	5.18	2.81	13.61
growth	3.77	5.54	1.49	19.16
early	2.83	6.13	1.23	32.38
shriveled early	1.5	2.91	0.5	30.22
tagged early	1.08	3.04	0.22	52.02

5. CONCLUSION

Physical Properties

The physical property investigation revealed that nut mass and nut dimensions are significantly less for early split than both non split and growth split nut types. But, the discriminate analysis showed that these properties alone cannot accurately classify the nuts into split types. Terminal velocity, moisture content of hulled and unhulled nuts, unhulled nut density, and hull friction factor properties were determined to be not significantly different for the split types.

Shell color is a promising property to use as a criteria for sorting early split nuts. Pistachio nuts are currently examined by electronic and human color sorters in commercial processing plants. It is likely that the existing color sorting procedures could remove most of the stained early split nuts. However, the color sorted nuts are often re-examined and a portion returned to the processing cycle. Before this is done, early split nuts might be able to be removed by detecting properties specific to early split nuts such as stains on the shell split perimeter, length and width product (or cross sectional area), yellowish hue on shell, or dominant stain location. However, many (approximately 10%) of the early split nut shells are not stained at all while significant portions of growth split (7%) nut shells are stained.

It is not known if the early split nuts with unstained shells are free of aflatoxin. This issue should be investigated before a sorting system to remove aflatoxin from pistachio nuts based on shell staining characteristics is implemented. Doster's report (1993) indicates that stained early split nuts are more likely to be contaminated with *Aspergillus flavus*. But, additional research would be needed to show that unstained early split nuts are free of aflatoxin.

Separating nuts based on shell color and staining characteristics has the advantage that it uses properties of hulled nuts for a sorting criteria. Hulled nuts pass through the processing plant at a slower rate than unhulled nuts. Unhulled nuts are delivered to the plant, hulled within a few hours, then dried and stored. The hulled nuts are taken from storage and processed throughout the year while unhulled nuts are all handled during the 4 to 6 week long harvest season. It is highly unlikely that any *Aspergillus* molds that

existed on an incoming nut would spread in properly maintained dry storage bins. Mojtahedi et al. (1978) showed that Iranian pistachios inoculated with *Aspergillus flavus* would not become contaminated with aflatoxin if stored below 25% relative humidity. Similar results have been shown for barley (Change et al., 1981).

The roller and needle device proved to be successful in separating growth split and early split nuts from non split nuts. This device is simple and could possibly be used as a preliminary sorting device before nuts are passed through a more rigorous and slower system such as a computer vision system.

Finally, this study confirms Doster's (1993) finding that early split nuts that split more than 30 days before harvest are prone to have shriveled hulls at harvest time.

An area for future work with the physical properties of pistachios would be to investigate the density of hulled nuts of the various split types. It would be useful to learn if hulled early split nuts consistently float as was seen with the 1993 tests. Furthermore, it would be more useful to learn if aflatoxin contaminated nuts float while others sink.

Hulling Properties

Differences in hulling characteristics of pistachio nuts can be used as a basis for removing early split nuts from the crop. The hulling properties results were confirmed by obtaining similar results for two years of study and from two different devices. This process has a comparable classification accuracy to a computer vision system. The hulling could be done as a bulk or batch process rather than by handling and inspecting individual nuts as would be required with a computer vision system. Furthermore, a differential hulling treatment could be applied to the nuts without drastically changing the current pistachio processing practices. It is likely that the hulling equipment currently in use at processing plants could be slightly modified to perform a differential hulling treatment. Nuts that do not hull would be removed by normal pistachio processing quality control equipment currently in use. In a processing plant, the nuts are dropped into water after hulling. The unhulled nuts tend to float and are skimmed off while most of the hulled nuts sink. The present study has shown that a large percentage of unhulled shriveled early split nuts would float. However, the density tests showed that unhulled early split nuts have a specific gravity of about 1, so floating the nuts in a brine solution may achieve better segregation of unhulled nuts from hulled nuts. Before final

packaging, pistachio nuts are also inspected by electronic color sorters and humans to remove unhulled nuts. It is likely that most unhulled nuts are removed at some point during normal processing. Finally, separation on the basis of hulling would probably not require changes with the harvesting and post harvest handling practices. Based on the hulling property investigation, it is likely that nuts which lose their hulls before arrival to the processing plant are not early split types.

An interesting area for further research would be to investigate if there is a correlation between hull adhesion and aflatoxin content. Perhaps the incorrectly classified early split nuts in a differential hulling treatment do not contain aflatoxin.

Computer Vision

The results of the computer vision investigation indicate that it is possible to detect early split pistachio nuts from non split and growth split pistachios with a high accuracy. The orientation devices can properly present the nuts to a camera for inspection. The orientation devices and detection algorithm are well suited for use with high speed line scan cameras. However, pistachio processing plants must hull nuts immediately after they are delivered to the plant to prevent backlog and shell staining. Pistachios delivered to the processing plant are typically processed at a rate of 2250 nuts per second. A computer vision system inspecting the hulls of nuts would likely be very expensive. However, given the high classification accuracy of the computer vision system, it may be useful to further grade nuts after a differential hulling process.

The condition of the hull upon arrival to the processing plant is important for a computer vision system. This would require some changes in the post harvest handling practices currently in use. The bulk handling equipment used on some harvesters remove or partially remove many hulls from the nuts. The computer vision algorithm used in this study assumed that the nut's hull remained intact after harvest. Although the algorithm could likely be modified to account for hulled nuts, the performance of the nut orientation devices would probably be degraded if required to deal with both hulled and unhulled nuts simultaneously.

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7. APPENDIX A:

Image processing program

/* pixel.c TOM PEARSON AUG 13, 1993

This program reads a 256 x 256 ASCII gray level image file and puts it into a two-dimensional array. Then the program examines every fourth column of the nut image (by assuming that the nut is represented by all pixels having gray levels less than 255). While examining the profile, it makes a record of the location of the minimum pixel in the profile. The program then calculates the mean of the profile (pmean) and the mean of a window 7 pixels wide with the minimum centered in the window 7 pixels wide and for pixels less than 255. The program locates the middle of the nut and compares the distance of the minimum intensity pixels to the middle line and the window mean with the profile mean. The image file name is read from a data file that contains a list of the images to be examined. The name of the data file is input at the beginning of the program at the appropriate prompt. Finally the pixel ratio, pr, is computed. Pixel ratio, pr, is the ratio of pixels less than the mean of the pixels in the split area divided by the total pixels in the image less than 255 **/.

```
#include <stdio.h>
#include <fcntl.h>
#include <stdlib.h>

main()
{
double pr;
int i, j, k, d, x, y, z, buffer[260], profile[260][260], minp[260], minrow[260],
width[260], wsum[260], psum[260], pmean[260], wmean[260], wcount[260],
topedge[260], middle[260], diff[260], maxx6, maxx8, pixels,
pixelwmd,maxxj,wm,length;

FILE *fd, *fo, *dataf;
char infile[80], adummy[80], data[40];

printf("type output file for DATA (15 characters max):  ");
scanf("%s", data);
fo = fopen(data, "w");

printf("\ntype image filename data file (type X to exit):  ");
scanf("%s",adummy);
dataf = fopen(adummy, "r");
```

```
infile[0] = 'a';

while (infile[0] != 'X')
{

fscanf(dataf,"%s",infile);

fd = fopen(infile,"r");

 if(fd==NULL)
  {
   printf("\nfile %s not found\n\n",infile);
   exit(-1);
  }

fscanf(fd,"\n\n%d %d %d\n%s\n", &x, &y, &z, adummy);

for(i=0; i<256; i=i+1)
{

 for(j=0; j<256; j=j+1)
 {
  fscanf(fd, "%d ",&buffer[j]);
 }
   fscanf(fd, "\n");

for(j=0; j<256; j=j+4)
{
profile[i][j] = buffer[j];
}
}

pixels = 0;
pixelwmd = 0;
wm = 0;
length = 0;

for(j=0; j<256; j=j+4)
{
minp[j] = 255;
minrow[j] = 0;
width[j] = 0;
wsum[j] = 0;
psum[j] = 0;
wcount[j] = 0;
diff[j] = 255;
topedge[j] = 255;
}
```

```
for(j=0; j<256; j=j+4)
{
 x = 0;
    for(i=20; i<235; i=i+1)
    {
        if(profile[i][j] < 255 && profile[i-1][j] == 255 && profile[i-10][j] == 255
                && x == 0)
        {
          topedge[j] = i;
          x=1;
        }


      if(profile[i][j]<minp[j])
          {
        minp[j] = profile[i][j];
        minrow[j] = i;
          }

          if(profile[i][j] < 255)
          {
          psum[j] = psum[j] + profile[i][j];
          width[j] = width[j] + 1;
          pixels = pixels + 1;
          }
    }  /* end of row "i" loop */

  for(k = minrow[j]-3; k <= minrow[j]+3; k=k+1)
    {
          if(profile[k][j] < 255)
          {
          wcount[j] = wcount[j] + 1;
          wsum[j] = wsum[j] + profile[k][j];
          }
    }

 if(minp[j] < 255)
  {
  middle[j] = topedge[j] + width[j]/2;
  diff[j] = middle[j] - minrow[j];
    diff[j] = abs(diff[j]);
  wmean[j] = wsum[j]/wcount[j];
          wm = wmean[j] + wm;
          length = length+ 1;
  pmean[j] = psum[j]/width[j];
  }
```

```
} /* end of column "j" loop */

wm = wm/length;

 maxx6 = 0;
i=0;
while(i < 230)
{
          x=0;
          while(diff[i] <= 13 && wmean[i] < 0.6*pmean[i])
          {
          x=x+1;
                    if(x>maxx6)
                    {
                    maxx6 = x;
                    maxxj = i;
                    }
          i = i + 4;
          }
  i = i +4;
}
 maxx8 = 0;
i=0;
while(i < 230)
{
          x=0;
          while(diff[i] <= 15 && wmean[i] < 0.8*pmean[i])
          {
          x=x+1;
                    if(x>maxx8)
                    {
                    maxx8 = x;
                    }
          i = i + 4;
          }
  i = i +4;
}

if (maxx6 > 5)
{
wm = 0;
for(j = maxxj-maxx6*4; j<=maxxj; j=j+4)
{
wm = wm + wmean[j];
}
wm = wm/(maxx6+1);
}
```

```
for (j=8; j<=240; j = j + 4)
{
  for (i=10; i<=240; i=i+1)
  {

 if (profile[i][j] <= wm)
        {
        pixelwmd = pixelwmd + 1;
        }
  }
}

pr = pixelwmd/(pixels+0.001);

printf("\n%s   %d  %d %d %4.3f",infile,maxx6,maxx8,wm,pr);
fprintf(fo,"\n%s,%d,%d,%4.3f",infile,maxx6,maxx8,pr);

}  /* end of while loop for input files */

fclose(fo);
fclose(dataf);
}  /* end of main */
```

VARIABLES

Integer Variables:

i, j, k loops.	Loop variable used for incrementing FOR loops and WHILE Usually "i" represents a row in the images and "j" represents columns.
x, y, z	Dummy variables used to count columns during while loops or to read unnecessary data from the images header files.
buffer[260]	Variable used to input a line of images data from the source ASCII file.
profile[260][260]	Array variable to temporarily store a working copy of the ASCII image file.
minp[260]	The minimum gray intensity of the profile.
minrow[260]	The row number corresponding to the minimum gray intensity of a profile.
width[260]	The width of the nut (vertical width) at a given column.

wsum[260]	The sum of the gray level intensities at in a widow +/- three pixels from the minimum intensity point in the profile.
psum[260]	The sum of the gray level pixels in a profile on the nut. Background not included.
pmean[260]	The mean gray level of the profile across the nut.
wmean[260]	The mean gray level of the column pixels +/- three pixels from the minimum point in the profile.
topedge[260]	The row where the top edge of the nut in a given column exists.
middle[260]	The row in which the midpoint of the nut is assumed to be located. middle[j] = topedge[j] + width[j]/2
diff[260]	The absolute value of the difference between the row number containing the minimum intensity value and the row number corresponding to the middle of the nut for a given profile.
maxx6	The maximum number of consecutive profiles where diff[j] <= 13 and wmean[j] < 0.6 * pmean[j].
maxx8	The maximum number of consecutive profiles where diff[j] <= 15 and wmean[j] < 0.8 * pmean[j].
pixels	The number of pixels with brightness below 255 in all the columns scanned.
pixelwmd	The number of pixels with intensities below the center window mean in all the columns scanned.
maxxj	The ending column of a detected split.
wm	The mean of the gray values in the center window for only those columns containing the detected split.
length	The length of the split measured in number of pixels.

File Pointers:

*fd	Pointer to the ASCII image file currently being examined.
*fo	Pointer to the data file where the output data is sent.

*dataf be	Pointer to the data file containing a list of the image file names to examined.

Character Variables:

infile[80]	String containing the name of the image being examined.
data[80]	string containing the name of the data output file.
adummy[80]	string containing the name of the data file listing of the image file names to be examined.

Double:

pr	pixel ratio = pixelwmd/pixels

8. APPENDIX B:

RGB TIFF To ASCII HSI conversion program

/* FILE: t2y.c DATE: 8-19-93 TOM PEARSON

This program converts a color 256 X 256 RGB TIFF file to a brightness (brightness from YIQ coordinates) ASCII file for loading into KBVision or other gray scale analysis. The file name for the input TIFF file should be no more than 25 characters. The separated brightness data will be stored in a file with the same name as the original but with a "y" (for brightness) appended to the end of the file name. The program reads the file names to be converted from a text data file. The name of the data file is requested at the start of the program. The header placed in front of the data to indicate the size of the file is:

```
7 256 256
{}
```

*/

```
#include <stdio.h>
#include <fcntl.h>
#include <stdlib.h>
#include <ctype.h>
#include <math.h>

main()
{

int fd, i, j, Y;

FILE *foy, *dataf;
unsigned char buffer[1000];
char outy[26], inbuff[25], databuff[25];

printf("type image intput name data file (type X to exit):  ");
scanf("%s", databuff);
dataf = fopen(databuff, "r");
inbuff[0] = 'a';

while (inbuff[0] != 'X')
```

```
{
fscanf(dataf, "%s",inbuff);


i=0;
while ( inbuff[i] !='\0')
    {
    outy[i]=inbuff[i];
    ++i;
    }
   outy[i]='y';

   ++i;
   outy[i]='\0';

/* CONVERT TO BRIGHTNESS AND PUT INTO ASCII FILE*/


foy = fopen(outy, "w");
fprintf(foy,"7 256 256\n{}\n");

fd = open(inbuff,O_RDONLY);
  if(fd== -1)
   {
    printf("\nfile %s not found",inbuff);
    exit(-1);
   }

read(fd,buffer,204);
for(j=0; j<256; j++)
 {
  read(fd,buffer,768);
  for(i=0; i<768; i += 3)
   {
          Y=(0.299*buffer[i+1] + 0.587*buffer[i+2] + 0.114*buffer[i])*1;

   fprintf(foy,"%d ",Y);
   }
  fprintf(foy,"\n");
 }

  fprintf(foy,"^D");
  fclose(foy);

printf("\n%s\n\n", outy);

}
fclose(dataf);
```

```
}
```

VARIABLES

integer variables:

i, j	Loop variables used in FOR and WHILE loops. Usually i corresponds to image rows and j corresponds to columns in the image.
Y	Brightness intensity value from the RGB values in the binary image.

File Pointers:

*foy	Pointer to the output brightness image in ASCII format.
*dataf	Pointer to the data file containing the list of binary image files to be converted.

Unsigned Character Variables:

buffer[1000]	String containing one line from the input binary image.

Character Variables:

outy[26]	String containing the name of the output ASCII image.
inbuff[25]	String to read in one line from data file containing image file names.
databuff[25]	String to read in name of data file containing names of images to be converted.

9. APPENDIX C:

Images and image processing data of pistachios used for image processing

In the data tables preceding the nut images, the following symbols are used:

MAXX6 = maximum consecutive adjacent profiles that met the early split criteria with the minimum intensity level below 60% of the mean profile intensity

MAXX8 = maximum consecutive adjacent profiles that met the early split criteria with the minimum intensity level below 80% of the mean profile intensity

PR = (pixels with intensities below split region mean)/(pixels with intensities above split region mean)

Length and width are the nut dimensions measured with calipers

Image name nomenclature:

The first set of numbers corresponds to the data that the nut was collected. The letters correspond to the split type: ES for early split, NS for non split, and GS for growth split. Finally, the last set of numbers correspond to the number given to the nut when it's physical properties were being evaluated. For example: 9-22 ES 43 means that the nut was collected during the 9-22 harvest, it is and early split nut, and it was tagged as nut 43 during the physical property evaluation.